LABORATORY SPECIMEN PREPARATION FOR COLD RECYCLED ASPHALT

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by

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SYNOPSIS

In Australia the use of Reclaimed Asphalt Pavement material (RAP) is increasing. Cold recycling has advantages over other recycling processes and conventional paving methods, making it a viable, cost-effective technique which preserves natural resources and reduces energy costs. The service life of RAP is known to be affected by the type and amount of recycling binder, compaction effort, curing time and temperature, amount of new aggregate and water content. Laboratory test procedures and/or in-situ tests are needed to assess the effects.

This project aims at finding a method for laboratory sample preparation for cold recycled asphalt which will produce specimens, in the shortest time, having properties similar to those of material laid in the field. In Phase One of the testing procedure the amount of new binder needed and the target compaction density were determined, and in Phase Two the curing temperature that accelerates the rejuvenating action to produce a higher resilient modulus in the shortest time was investigated. Specimens were cured at different temperatures and tested for resilient modulus. Core specimens were to be taken from cold recycled asphalt pavements for comparison, but this did not eventuate due to time constraints and the expense involved.

It was found that maximum resilient modulus was obtained at 90°C after 24 hours curing, but a curing temperature of 60°C is recommended as it is more economical than 90°C, and because other asphalt tests (creep and Marshall stability) are performed at 60°C, making this temperature more practical. At the higher temperatures, resilient modulus increased rapidly in the early stages of the curing process but at room temperature, specimens required 2 weeks curing in order to be tested. After 24 hours curing, no significant change in viscosity was observed at any temperature, but viscosity increased thereafter with time and more so at higher temperature.

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CHAPTER 1 *INTRODUCTION*

1.1 STATEMENT OF PROBLEM

Australia is a road transport-dominated country and it is likely that there will continue to be an increasing demand for the construction and maintenance of bituminous road pavements. The recycling of asphalt pavements not only preserves natural resources, but also offers reduced costs in transportation and the conservation of energy and of binders.

As cities grow, the necessity for the construction of roads increases. Also as existing resources diminish, quarries are located further away from demand areas, thereby increasing hauling costs. As sources of crushed rock become more distant from cities, it will become more costly. Recycling, therefore, can be a viable, cost-effective technique.

The continued increase in the amount of bituminous surfaced roads in Australia is a result of the progressive upgrading of the road network rather than the creation of new roads. Australia has now about 250,000km of bitumen or concrete surfaced public roads.

According to Bowering (1990), between 190,000 and 290,000 tonnes of reclaimed asphalt is produced annually in Australia, from which approximately 48,000 to 70,000 tonnes is used as recycled asphalt. The remainder is downgraded for use as sub-base, base, shoulder material or clean fill, or alternatively stockpiled for future use. In 1989 for instance, 35,000 tonnes of reclaimed asphalt was crushed and screened for use as a clean fill for garbage tipping control (Bowering, 1990).

Because of the increasing availability of Reclaimed Asphalt Pavement (RAP), it can provide a steady source of high quality pavement material, which also results in less dumping of the material into landfills. The recycling of bituminous pavements also reduces the need to quarry, crush and screen natural aggregates, which are finite resources.

Throughout the world, recycling of all types of pavements is growing. Test results and overseas experience have shown that road bases consisting of 100% reclaimed asphalt are suitable for future large scale use in road construction.

Before using new or recycled pavement materials, samples of them must be mixed with the intended binder (or binders, if a choice is to be made) and tested to establish that a satisfactory mix can be produced. The most important properties of bound pavement materials are strength, elasticity and durability. These are investigated by means of laboratory tests such as Marshall stability and flow, resilient modulus and strength. In order to ensure as much as possible that the laboratory test specimens resemble the material after it has been laid, compacted and cured in the field it is necessary to produce uniform specimens that will have engineering properties similar to those of cores taken from pavements laid in the field.

Preparation procedures for laboratory specimens vary throughout the world. Although the differences may not be large, little is known of their effects on test results. In Australia, a specific preparation procedure for laboratory specimens of cold recycled asphalt has not yet been developed. Many trials have been done but no official reports have been produced.

The use of mechanistic pavement design procedures is becoming increasingly widespread (Molenaar *et al*, 1992) and, for this, values of resilient modulus, which is determined in a repeated load testing apparatus on compacted specimens, are required. Compaction of test specimens of cold recycled asphalt is difficult and improved techniques are needed. A compactor using a gyratory action is now in common use, and investigations of its behaviour are under way (Caltabiano and Waters, 1991; Kadar, 1992).

Material properties of RAP are dependent on the properties of the old binder and aggregate in the mix. However, these properties can be modified by adding binders which can restore the original bitumen characteristics. All these aspects were studied or taken into consideration in this research.

1.2 AIM

This study aimed at finding a method of preparation of laboratory test specimens of RAP which would result in their having properties closely resembling those of the material when laid in the field.

Originally, it was intended to compare the behaviour of laboratory specimens with cores from actual pavements. Unfortunately this was not possible due to time constraints and expenses involved in the coring process. It was also intended to examine creep, fatigue and strength behaviour of cold recycled bituminous road pavement materials. However, because of time constraints and equipment availability, resilient modulus and binder viscosity were the main properties measured.

1.3 THESIS OUTLINE

The thesis consists of seven chapters which are laid out in the following manner:

In Chapter One the problem is stated, and reasons are given for the importance of recycling asphalt pavements, and of the preparation of laboratory test specimens which replicate field behaviour. It also gives the general aims for this research.

Chapter Two reviews the literature which is relevant to the research.

Chapter Three presents the methodology followed, as well as the equipment used for testing throughout the research.

Chapter Four describes in detail the testing procedures used and the reasons for using them. The information provided is carefully described so that the reader can carry out any comparative testing.

Chapter Five presents all test results obtained.

Chapter Six describes in a comparative way all results obtained, not only between the research procedures, but also with relevant results obtained by other authors. Comments on similarities and differences are also made.

Finally, Chapter Seven states the recommended testing procedure which should ensure the most practical, cost effective and fastest way of obtaining information. This chapter also presents some suggestions for further research in this area.

CHAPTER 2 *LITERATURE REVIEW*

2.1 INTRODUCTION

Asphalt recycling may be defined as the re-use after suitable processing of bituminous-bound material after it has served its first intended purpose. The processed material can be used in a variety of applications, such as road pavements, footpaths, and tennis courts.

According to Epps (1990), the recycling of asphalt dates from as early as 1915. However, more applications have been found in the last 15-20 years, mainly in the United States. Currently, several major research projects are under way around the world to develop and/or determine the most effective uses of Reclaimed Asphalt Pavement (RAP). RAP can be recycled up to 100% and has many advantages over conventional pavements, among which are:

1. Cost savings of approximately 30% compared with the production of hot mixes (Cohen *et al*, 1989). These savings are in materials and transportation as well as energy costs (fuel consumption and heating of mix) (APPA, 1991).
2. Air pollution reduction as compared with both hot mixes and cold cutback mixes.
3. Reduction in solid waste disposal.
4. Reduction in the use of fresh materials.
5. Versatility of preparation and construction - for example, the material can be prepared in a central plant, or a mobile plant, or in-situ.

Bowering (1990) stated that, in Australia, pavements have been recycled since the late 1970s. However, over the last 5 years there has been increased activity in this field, especially in use for road construction.

2.2 RECYCLING METHODS

The recycling of pavements involves the lifting and treating of a distressed pavement material and the use of all or part of it in another pavement. After it is lifted and crushed, whether in-situ or in a plant, it is mixed with a binder, which may be bitumen or cement. Pavements showing extensive and severe cracking, stripping, potholes, rutting and brittleness failures due to ageing can be recycled. The methods most commonly used, according to the Asphalt Emulsion Manufacturers Association (AEMA, 1985), are:

1. Hot and Warm Central Plant.
2. Cold Central Plant.
3. Hot In-situ or Hot In-Place.
4. Cold In-situ or Cold In-Place.
5. Full Depth Stabilisation.

Hot and Warm Central Plant involves the removal of pavements by means of a rotary drum milling machine. The removed material is then transported to a central plant where it is crushed and screened to the required size and blended warm or hot with the added binder. The crushed material is later returned to the construction site where it is placed like hot mix asphalt.

With this method a much denser mat is produced. Most pavement deformations are corrected, and in some cases skid resistance is improved. The drawbacks of this method are the high energy costs involved, the requirement of traffic control after construction and hazards in dealing with the heating apparatus.

The Cold Central Plant process consists of the reuse of asphalt surfaces and, in some cases, the underlying base material. The removed pavement is transported to the central plant where it is crushed and screened to the required size. It is stockpiled for later use or transported back to the construction site. Emulsion is usually added at the plant, but sometimes it is sprayed onto the material after being placed.

In some instances, virgin aggregate is added to improve grading, as with this method the aggregate is sometimes broken down even further, or to increase the pavement thickness. This method is economical for large projects, and also allows the correction of pavement problems associated with underlying base materials.

The Hot In-situ process needs special equipment or machinery (a recycling train) which heats and softens the existing material in order to allow it to be scarified to the required depth. It is then mixed with the binder (emulsions/cutbacks) and later compacted by means of heavy machinery.

This method is sometimes used to improve aggregate grading and the bitumen content of the existing pavement. Flexibility and adhesion of the binder are improved when recycling agents are used. With this method, rutting and potholes are filled, shoving and corrugations are levelled, and crown shape and drainage are corrected. A disadvantage of this method is the limited depth of treatment.

Cold In-situ recycling is done using a rotary drum milling machine to provide a precise depth of cut so as to utilise only the asphalt pavement. The cut material is passed into an automatic self-propelled asphalt paver which mixes the material with the binder and then replaces it.

This method corrects minor irregularities in the pavement. Surface cracks are completely removed. However, the design life of the recycled pavement may not be as long as that of a new pavement because, the limited depth of cut does not allow problems in the base or sub-base materials to be addressed. Rutting and incorrect crossfall can also be corrected with this method.

Full Depth Stabilisation process consists of removing the full depth of asphalt pavement and untreated underlaying layers, pulverising them, and mixing with binders and, in some cases, new aggregate. This mix is later placed back again, compacted and resurfaced with an bituminous cold mix or other surface treatments.

The selection of the method to use depends on the physical condition of the pavement, the equipment available and finally the processing costs. Of the methods described above, Cold In-situ and Cold Central Plant are the most common, followed by Full Depth Stabilisation, with Hot recycling processes being the least common (Finn, 1992).

Countries like the United States, Germany, France, Israel, Great Britain and Canada have reported Cold In Place recycling as the most effective method of recycling. This is due to the fact that it is more environmentally friendly as no gaseous emissions (known as blue smoke) are produced. Also, Cold recycling is less hazardous as the equipment does not require any heat. Finally Cold In Place is more energy efficient. In Australia, Hot In-situ asphalt recycling is known as HIPAR. Cold asphalt recycling is still being developed.

2.3 SELECTION OF PAVEMENTS FOR RECYCLING

Asphalt pavements have a finite life expectancy which is influenced by traffic loads, the aggregate size and type, bitumen type and content, the climate in the area, underlying layers and, of course, the pavement thickness. The ultimate pavement design can be influenced by all these factors (Hunter, 1994).

Kennedy *et al* (1985) classify pavement distress into two classes - brittle and non-brittle. Brittle failures occur when axle loads induce tensile stresses that, acting on oxidised asphalt, produce cracking. When a pavement with this type of distress is to be recycled, a new binder and/or a recycling agent (or rejuvenator) is used to restore the bitumen's original viscosity.

Non-brittle failures occur due to the deformation or lateral movement of the underlying layers (base and sub-base courses) of the pavement. This occurs because of a high bitumen content in the original mix, producing rutting, shoving, corrugations and/or bleeding. If the pavement is to be recycled, the amount and type of rejuvenator to be added must be carefully controlled.

Road pavements showing most types of distress, or which need to be upgraded, are usually recycled. It is therefore important to identify the reason for the distress so that an adequate mix and, therefore, a satisfactory pavement performance is achieved. Also, the cause of pavement distress will determine the type of additive to be added to the RAP. For example, if a pavement showing excessive cracking is to be recycled, it is necessary to restore the old binder to its original viscosity, or to an acceptable one, by adding new bitumen and/or a recycling agent. Care should be taken with the amount added since too much additive will result in an unstable mix. Pavements that show excessive stripping need to be treated by the addition of anti-stripping agents and sometimes lime (Kennedy *et al*, 1985).

Pavements showing rutting, shoving, bleeding or corrugations, due to a low bitumen viscosity or excessive bitumen content, can be recycled. To correct these problems, new aggregate may be added prior to, or during, the recycling process. This will make the mix drier and will incorporate more angular aggregate particles that will increase the stability of the mix.

The geographical and climatic location of a pavement also plays an important part in its performance. Overseas experience reported by Rogge *et al* (1992) and Cohen *et al* (1989) indicate that cores taken from recycled pavements using emulsions and constructed at the same time but in different locations, have given rather different test results. For example, pavements perform well when constructed in high desert areas or places with very dry climate and abundant sunlight. This is because, at high temperatures, rapid moisture evaporation takes place accelerating the rejuvenating action of the emulsion with the old binder, and pavement strength is attained rapidly.

The opposite occurs for recycled pavements which are constructed in heavily forested areas where excessive shade and low temperatures reduce the rate of moisture evaporation from the emulsion, slowing the reaction of the emulsion with the old binder. If recycling is to be done in these areas, a reduction in water content and 24 hour traffic control is recommended (Rogge *et al,* 1992).

2.4 TESTS COMMONLY PERFORMED

Tests and procedures for determining the physical and mechanical properties of cold recycled asphalt mixtures which are used by various organisations, are described in Appendix A. These include Abson recovery, Marshall stability and flow, Hveem stability and cohesion, kneading compaction, Centrifuge Kerosene Equivalent, gyratory shear compaction, viscosity, penetration, resilient modulus, coating test, repeated load indirect tensile test, vacuum saturation and fatigue test.

2.5 MIX DESIGN PROCEDURE, SAMPLING AND TESTING TECHNIQUES

Procedures for mix design and laboratory specimen preparation vary throughout the world. However, in countries that do Cold In Place Recycling, the RAP is analysed before and after construction for bitumen content and aggregate grading. New aggregate may also be added to the mix to provide additional thickness to the pavement, to correct grading or to decrease the amount of new binder required.

According to Epps (1990) and Cohen *et al* (1989), most states in the US, and most other countries, have developed mix design procedures for recycled asphalt, but a uniform method has not emerged. Common basic steps in many mix design procedures include:

1. Sampling - before and after recycling the pavement.
2. Processing of samples separating particles by heat-softening or crushing mechanically to perform sieve analysis of RAP and clean aggregate.

3. Determining bitumen content and physical properties of bitumen such as viscosity and penetration.
4. Selecting type and amount of new aggregate.
5. Estimating bitumen demand.
6. Selecting type and amount of recycling agent.
7. Testing field and laboratory prepared specimens of trial mix.

Among the countries, states, cities and organisations which have reported using Cold In Place recycling or which have a mix design procedure are California, Oregon, Pennsylvania, Texas, New Mexico, Chevron Inc., Asphalt Institute, US Navy (Epps, 1990), Indiana (Tia *et al* 1983), Ontario (Emery 1993), Israel (Cohen *et al* 1989), the United Kingdom (Stock 1987) and Germany. Table 2.1 summarises the mix design procedures, and the sampling and testing techniques used by some of these organisations.

The methods are generally very similar. All but one use the Marshall and Hveem tests. Kneading or gyratory compaction is used by some, while others use the Marshall method. The main differences are in the addition of new aggregate, and in curing time and temperatures. Some of the mix design procedures are discussed in Appendix B.

ORGANISATION	SAMPLING	DETERMINATION OF RAP PROPERTIES	ADDITION OF NEW AGGREGATE	DETERMINATION OF EMULSION REQUIREMENT	MIXING	COMPACTION	CURING	TESTING
STATE OF CALIFORNIA	• Pavement cores. • Large pieces crushed in the laboratory.	• Bitumen content by Abson recovery test. • Aggregate grading. • Viscosity from Abson recovered bitumen.	• None	• Done by means of the surface area of aggregate.	• Mixing is done by adding 2% water and different emulsion contents.	• By kneading compactor at 60°C.	• Mixed specimens are cured loose at 60°C for 16 hours.	• Hveem stability at 60°C. • Air void determination. • Specific gravity.
STATE OF PENNSYLVANIA	• Pavement cores. • Bags from stockpile.	• Bitumen content by Abson recovery test. • Aggregate grading. • Viscosity at 60°C. • Penetration at 25°C.	• Up to 50%.	• Determined by total bitumen needed by the RAP aggregate after extraction, and calculated by means of the aggregate surface area.	• Mixing done by hand. • Emulsion content kept constant at 2.5% by weight and heated to 60°C. • 3% MC is used with increments of 1%	• Compaction at 23°C using a Marshall hammer applying 75 blows per face.	• Loose curing at 41°C for 45 minutes. • Mould curing at 23°C for 15 to 24 hours. • Extruded specimens cured at 40°C for 3 days	• Resilient modulus at 25°C. • Marshall stability and flow. • Bulk specific gravity. • Vacuum saturation and soaking at 25°C to determine modulus.
STATE OF OREGON	• Field samples reduced to 100% passing the 25mm sieve	• Bitumen content by Abson recovery test. • Aggregate grading. • Absolute viscosity at 60°C. • Penetration at 25°C. • RAP grading.	• Not mentioned	• Estimated using absolute viscosity and penetration charts from previous projects or by established formula.	• Hand mixed with preheated emulsion at 60°C for 1 hour. • Water contents of 0.5%, 1.0% and, 1.5% are used.	• Kneading compaction at 60°C applying 50 blows. • Re-compaction using kneading compactor at 60°C applying 50 blows.	• Loose curing at 60°C for 1 hour. • Mould curing at 60°C overnight. • Further mould curing at 60°C for 24 hours. • Extruded specimens cured at room temperature for 72 hours.	• Hveem stability • Resilient modulus

Table 2.1 **Summary of testing procedures performed or studied by different organisations.**

ORGANISATION	SAMPLING	DETERMINATION OF RAP PROPERTIES	ADDITION OF NEW AGGREGATE	DETERMINATION OF EMULSION REQUIREMENT	MIXING	COMPACTION	CURING	TESTING
PURDUE UNIVERSITY INDIANA	• Not stated	• Bitumen content. • Clean aggregate grading	• New aggregate is added depending on clean aggregate grading.	• Optimum emulsion content determined by a gyratory compactor machine.	• Mechanically mixed for 2 minutes and half a minute hand mixing.	• By gyratory compactor using of 20 revolutions at 1400kPa and 60 revolutions at 1400kPa.	• Mould curing for 24 hours at room temperature or 60°C.	• Unit weight. • Resilient modulus • Hveem R-value • Marshall stability and flow.
CHEVRON USA INC.	• Crushed material to produce laboratory specimens.	• Bitumen content. • Aggregate grading. • Viscosity at 60°C or penetration at 25°C. • Viscosity at 135°C.	• New aggregate added if required.	Determined by either: • Centrifuge kerosene equivalent or, • aggregate surface area formula.	• Mixed at different recycling agent contents.	• By kneading compactor applying 10 to 50 blows per face and 178kN plunger method at 73°C.	• Mould curing at 23°C for 24 hours. • Final mould curing at 23° C for 72 hours. • Water soaked curing under vacuum saturation at 100mm mercury.	After final curing: • Hveem resistance and cohesiometer. • Resilient modulus. • 4 days vacuum desiccation at 10-20mm mercury.
ASPHALT INSTITUTE	• Obtained randomly from the field.	• Bitumen content. • Aggregate grading	• New aggregate only added to correct RAP grading.	• Emulsion content determined by means of an aggregate surface area formula presented in the Asphalt Institute Manual No. 21.	• Determined by the agency using the method.			

Table 2.1 (Continued)

ORGANISATION	SAMPLING	DETERMINATION OF RAP PROPERTIES	ADDITION OF NEW AGGREGATE	DETERMINATION OF EMULSION REQUIREMENT	MIXING	COMPACTION	CURING	TESTING
TEXAS	• Obtained from different projects to determine binder consistency. These samples are later divided into laboratory specimens, cores and field mixed specimens.	• Aggregate grading • Bitumen content • Aggregate grading after addition of new aggregate. • Maximum particle size after pulverisation.	• New aggregate is added if necessary.	• No specific formula is stated. Different emulsions are used and are selected depending on properties achieved, such as viscosity and penetration.	• Aggregate and desired emulsion are heated and mixed together for 3 minutes. • Extracted bitumen is mixed with various additives to determine best combination.	• Laboratory specimens are compacted using the Texas gyratory shear compactor.	• Mixed specimens were stored in a temperature controlled oven to reach testing temperature of 24°C.	• Specimens were tested to determine fatigue, tensile strength and static modulus of elasticity using the static and repeated-load indirect tensile tests.
WITCO CORPORATION	• A representative sample of approximately 10kg.	• Bitumen content • Aggregate grading. • Penetration at 25°C or viscosity at 60°C.	• Not mentioned.	• Determined by either the centrifuge kerosene equivalent or by a given formula. The amount to add equals bitumen demand minus bitumen content	• Mixing with required rejuvenator content.	• By means of a Marshall compactor.	• Not stated.	• Marshall stability. • Hveem stability.

Table 2.1 (Continued)

ORGANISATION	SAMPLING	DETERMINATION OF RAP PROPERTIES	ADDITION OF NEW AGGREGATE	DETERMINATION OF EMULSION REQUIREMENT	MIXING	COMPACTION	CURING	TESTING
ISRAEL	• Representative sample from a project from which 70% RAP was used.	• Evaluation of layer thickness and type of material present. • RAP aggregate grading. • Bitumen content.	• 20% new aggregate and 10% quarry sand was added	• Four emulsion contents were used (4%, 5%, 6% and 7%).	• Four emulsified recycling agents contents were added cold to the aggregate with 1% IMC addition and mixed by hand with a spoon for 60 sec.	• Marshall compaction using 75 blows on each face.	• Wet aggregagte left to stand at 22°C for 10 to 15 minutes. • Mould curing at 60°C for 16 hrs. • Mould curing at 22°C for 3 and 10 days before testing.	• Marshall testing at 60°C after 3 and 10 days curing at 22°C. From the test, Marshall stability, Marshall flow and Marshall stiffness were determined.
ONTARIO	• Representative sample from millings or from coring.	• Moisture content. • Bitumen content. • Grading. • Penetration.	• New aggregate is used if necessary.	• Emulsion content is determined from plots of density, air voids, stability at 22° and 60°C against the percentages of emulsion used.	• Mixing is done with five different emulsion contents heated at 60°C at estimated field moisture content.	• Compaction using Marshall hammer applying 50 blows per face after loose curing. • Re-compaction applying 25 blows per face.	• Loose curing at 60°C for one hour. • Mould curing overnight at 60 °C. • Mould curing on their side for 24 hours at 60°C.	• Marshall stability and flow at 22°C and at 60°C. • Bulk relative density

Table 2.1 (Continued)

2.6 RESEARCH AND FINDINGS ON THE PROPERTIES OF MIXES

Research studies conducted in the United States, Canada, and Israel have provided basic information on mechanical properties of the cold recycled asphalt material.

Tia *et al* (1983) evaluated the effect of three different aggregate grading on the behaviour of recycled asphalt mixtures. The study consisted of the preparation of various percentages of crushed stone, virgin aggregate and reclaimed pavement material, blended to three gradings with two types of binders. The findings from this study showed a variation of results in the tested specimens. These variations appear to be due to the differences in surface areas of the gradings used, which at the same time affected the binder content and, therefore, some properties of the final mix, such as density and strength. The study also showed the effects of curing time, binder content and compaction on resilient modulus. An increase in modulus was observed in the first seven days, and continued to be constant thereafter.

Cohen *et al* (1989) conducted research on a public road in Israel to investigate the performance of a pavement re-constructed with a cold recycled emulsified bitumen mixture. A laboratory mix design was done before construction. From the laboratory results it was found that, at an optimum binder content, high density and stability were achieved. The fact that specimens were air-cured did not produce any effect on the results obtained. The extracted bitumen, however, showed a great variation in penetration and ductility between specimens.

Test results obtained from Marshall stability test showed that field compaction gave high and uniform density. The initial Marshall stability was low but a rapid increase in stability was achieved with time, due to the evaporation of water and the volatile components of the bitumen. Durability tests (vacuum saturation and freeze-thaw cycles) showed that the cold recycled mix achieved high durability potential and had high resistance to damaging weather effects.

A study was performed in the state of Nevada (Epps, 1990), on the relationships between resilient modulus and curing time and temperature. After 14 days curing, a high resilient modulus was achieved. Freeze-thaw cycles showed damaging effects on the recycled material. On the other hand, two hours soaking showed no damage to the specimens. Marshall stability and flow was performed on both laboratory and field specimens. Higher stability values were achieved with longer curing times. Low stability values were the result of poor curing and of water entering the pavement.

The studies conducted in the state of Michigan and shown in Epps (1990) indicated the relationships between Marshall properties, curing time, binder content, binder type, and soaking of specimens. From the testing results, the following trends were observed:

- Specimens that were water soaked took 30 days to reach maximum Marshall stability, whereas unsoaked specimens reached maximum Marshall stability after 48 hours.
- During soaking, specimens showed a loss of strength and one week curing was required as a minimum in order to regain strength and resistance to water damage.

Tia *et al* (1983) found that Hveem stability decreases with an increase in binder content and with a higher compactive effort, whereas higher resilient modulus and Marshall stabilities were obtained with higher compactive efforts. Also, resilient modulus, and Hveem and Marshall stabilities increased with curing time.

An increase in resilient modulus was obtained with an increase in the curing period, taking between 20 to 100 days to reach peak value. These values varied depending on the curing temperature, recycling agent content and length of curing period.

Santucci and Hayashida (1983) found that strength or resilient modulus increased rapidly during the early stages of the curing period. This was due to a loss of water and/or solvent from the emulsified agent which Santucci and Hayashida called breaking of the emulsion. The breaking of the emulsion is depicted by the darker areas in figure 2.1. The lighter area depicted in figure 2.1 represent smaller changes in mass and resilient modulus. These smaller changes (either increases or decreases) are defined by Santucci and Hayashida as fluxing.

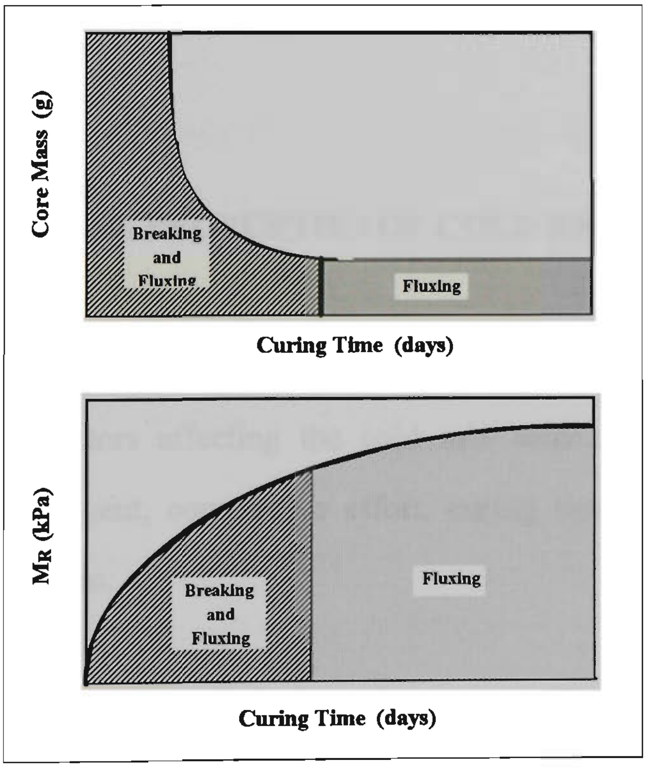

Figure 2.1 **Development of modulus and loss of mass with curing time as depicted by Santucci and Hayashida (1983).**

The properties of the recycling agent also play an important part in the development of modulus. High viscosity recycling agents seem to give high resilient modulus values. On the other hand, recycling agents containing solvents in their composition tend to produce low resilient modulus values, in which case a longer curing time is required to achieve higher strength.

The amount of recycling agent also affects the resilient modulus value. High recycling agent contents produce mixes with a very low resilient modulus value, leading to low stabilities and low void contents, and which are prone to permanent deformation or rutting in the field.

Fatigue test studies reported by Rogge *et al* (1992) and Hicks *et al* (1989) showed that fatigue life of cored specimens increased due to the increase in density with additional curing time. Fatigue lives obtained from cold recycled mixes were comparable to those of a conventional mix, i.e. 10,000 to 50,000 repetitions to failure, as reported.

2.7 FACTORS AFFECTING PROPERTIES OF COLD RECYCLED MIXES

From the studies published on cold recycling of pavement which were examined for this thesis, six factors affecting the cold mix were commonly reported. These are: recycling agent, compactive effort, curing time, temperature, new aggregate, water addition.

2.7.1 Recycling Agent

Recycling agents are added to recycled mixtures to rejuvenate the old binder and produce a mix that will comply with the design requirements. The rejuvenation of the old binder depends on time, temperature and compaction.

The type and amount of recycling agent added is the most important factor in both short-term and long-term behaviours of the mix and should be selected depending on the type of pavement distress.

2.7.2 Compactive Effort

Compactive effort and curing time are the most critical factors affecting the mix. Laboratory compaction and curing time will represent approximately what happens in the field. Tia *et al* (1983) say that most of the effects of the recycling agent on the mix are observed during compaction. It was observed that, at a higher compactive effort, the old binder and the recycling agent will blend more effectively. This was shown by the higher resilient modulus and stabilities obtained at the highest compactive effort.

In the work done in this thesis it was observed that the blending of the old bitumen and the added recycling agent did not take place during compaction but throughout the mixing and curing process. On the other hand, higher resilient modulus were obtained with curing time. At higher compactive efforts a denser material will result which, in time, will produce higher modulus.

Laboratory specimens can be compacted to the same density/percentage voids as that used in road pavements but, as time increases, it is expected that road pavements will become denser (less percentage voids) due to traffic.

2.7.3 Curing Time

The curing time required for the recycled mixture will depend on the type of recycling agent used. Tia *et al* (1983) state that, for most of the recycling agents, curing time is crucial. For example, the stiffness of the mix will increase with time because water and volatile fractions evaporate.

Resilient modulus, stability and water resistance of the mix increase with curing time. In cases where a very old pavement is to be recycled, large amounts of recycling agents are used to soften it. In such cases, the initial stiffness and stability of the mixture tend to be very low and it will require a longer curing time for the mix to reach the desirable strength.

2.7.4 Curing Temperature

Temperature also plays a very important role in the properties of the recycled mixes. It has been observed that optimum binder content usually decreases when temperature increases (Tia *et al,* 1983).

Temperature plays an important role during curing and throughout the service life of a road pavement. Rogge *et al* (1992) state that when temperature is low the rejuvenating action takes longer to occur, as water evaporation is very slow, requiring weeks for complete curing to take place. When dry weather and high temperatures occur, water evaporates rapidly and the pavement achieves high strength a few hours after compaction.

2.7.5 New Aggregate

The use of new aggregate in recycled asphalt mixtures will depend on the design requirements. The purpose of adding virgin aggregate is to improve the grading of the cold recycled material or to reduce the amount of recycling agent added, making the mix drier (Tia *et al* , 1983).

2.7.6 Water Addition

Water is normally added to the cold recycled material to facilitate the mixing and compaction process. Normally, 1 to 2% of water is added, but this depends on the initial moisture content of the RAP. If larger amounts of water are added, the mix may be too wet and therefore a longer curing time will be required to reach maximum strength.

The addition of water also affects the density of the mix after compaction. Large amounts of water will produce high void contents, which in time will reduce the pavement service life by making it less durable and prone to weather damage.

2.8 SUMMARY

It was found that the examined preparation procedures for laboratory specimens of cold recycled bituminous pavements around the world were similar. In Australia, preparation procedures for cold recycling of bituminous pavements have not been discovered in the literature.

Recently, the use of the gyratory compactor for preparation of bituminous pavement specimens has become very popular in Australia, the USA and Germany. The results of tests performed on gyratory compacted specimens are similar to those obtained on field cores (Kennedy and Perez (1978) and Tia *et al*

(1983)). Some of the factors which may affect the properties of compacted specimens are:

- The amount of added rejuvenating agent.
- Moisture content of mixture at the time of compaction.
- Curing time required before and after compaction.
- Temperature required to cure samples and temperature used during compaction.
- Amount of fines in mixture.
- Size of reclaimed aggregate.

CHAPTER 3 *METHODOLOGY AND EQUIPMENT*

3.1 METHODOLOGY

The methodology for this research is presented below, indicating changes made during the study.

3.1.1 Preparation Procedures

The various preparation procedures found in the literature were to be summarised, and common themes identified if they existed. Representative procedures were to be chosen, and specimens prepared in accordance with them. These specimens were to be tested for strength and modulus and the effects of differences in preparation noted.

It was found from the literature review that most of the procedures followed, or were based on, the method of the US Asphalt Institute. The main differences were in the calculation of the binder demand, where various methods were used. This was not the expected outcome of the literature review, so a change of approach was needed. The Asphalt Institute method was adopted, but a curing period using different temperatures was added prior to testing for modulus.

3.1.2 Gyratory Compactor

Various methods of working the gyratory compactor were to be tried and their effects evaluated. It was proposed to investigate whether target density or target height was preferable, the effect of number of cycles, and the effect of different temperatures. With the compactor actually used, target height was not an option and, therefore, a target density was chosen (the maximum dry density obtained at Optimum Moisture Content) which all specimens where required to meet. Compacting to a given number of cycles would produce specimens with different densities, and compacting at different temperatures would increase the number of variables affecting the modulus value.

3.1.3 Core Specimens

Cores from actual pavements were to be taken and tested, and specimens from the same material were to be prepared in different ways and tested for modulus to see which best replicated the behaviour of the field specimens. This would give an indication of the laboratory preparation methods that best matched the field conditions. However, cores from pavements were unable to be taken and tested because of lack of time and the cost involved.

It was decided to base the investigation on a sample of RAP from a stockpile of freshly crushed material, and to assume that the laboratory preparation procedure with curing at 25°C would best simulate conditions in real pavement and produce values of resilient modulus similar to those which would be achieved in them.

3.1.4 Mix Proportions

Mixes containing different proportions of additives, crushed recycled asphalt and virgin aggregate, were to be compacted to determine their strength when tested under compression.

Specimens were not mixed using different proportions of additives and crushed recycled asphalt. All specimens were produced using 100% RAP and the same percentage of rejuvenator, and were tested using the MATerial Testing Apparatus (MATTA) for modulus only, since it is a non-destructive test. This allowed the measurement of change in modulus with time after compaction on the same specimens, as it was thought that this would reduce the scatter of results. This also reduced the time needed for specimen preparation, the amount of rejuvenator required, and the equipment time required. A full description of the MATTA is presented in Chapter 4, Section 4.4.4.1 and is depicted in figure 4.4.

3.1.5 Resilient Modulus Testing

Specimens were to be tested in the Repeated Triaxial Load (RTL) apparatus to determine permanent deformation and resilient modulus values. Specimens were not tested in the RTL apparatus as it destroys the specimen and it was required to test specimens continuously. Specimens were therefore tested in the MATTA in Repeated Load Indirect Tensile (RLIT) mode to determine resilient modulus and the resulting horizontal strain. The test consists of the application of repeated loads across a specimen diameter measuring lateral deformation produced by the applied stress in order to calculate resilient modulus.

3.1.6 Other Tests

Other tests were to be carried out to determine physical properties such as shrinkage and creep and also rutting of the recycled asphalt material. However, these tests were discarded from the testing program because they require the use of the relevant testing apparatus for longer periods of time than were available in the laboratory.

3.2 EQUIPMENT

3.2.1 Apparatus

The pressure filter method was used for the bitumen extraction rather than the centrifugal extraction method, because the equipment and other accessories used are considerably cheaper and readily available. Also, the apparatus requires lower maintenance and is more environmental friendly as the solvent can be recovered, rather than allowing it to evaporate as in the centrifugal method. Although the centrifugal extraction method is more accurate than the pressure filter method, the difference is minimal. The pressure filter method and the centrifugal extraction method test procedures are covered by AS 2891.3.3 (1991) and AS 2891.3.2 respectively.

The particle size analysis of RAP and clean aggregate were performed in accordance with AS 1141.11 (1980) *Particle Size Distribution by Dry Sieving.* The sieves sizes used were: 19.0, 13.2, 9.5, 6.7, 4.75, 2.36 and 1.18mm and 600, 300, 150 and 75μm.

The optimum moisture content and dry density were determined by means of the Australian Standard Modified compaction test in accordance with AS 1289.E2.1 (1977) and Vic Roads test method RC 315.01 (1991). Other tests performed were the void-free bulk density and viscosity tests. Viscosity was determined by means of a sliding plate micro-viscometer at a temperature of 45°C. These tests are further described in Chapter 4.

The compaction and modulus determination of specimens were done using an Intensive Compaction Test gyratory compactor (ICT) and the MATerial Testing Apparatus (MATTA). A full description of the apparatus and the testing procedure is described in Chapter 4. A gyratory compactor was used rather than any other type because it gives to the aggregate a similar orientation to that obtained in field compaction. It is also becoming widely used in Australia for the compaction of bituminous specimens, as well as in the USA.

The Intensive Compaction Test gyratory compactor (ICT) was used in this research. This compactor, rather than the gyratory compactor (Gyropac) developed by Industrial Processing Controls (IPC), was used because it was available at the time required. The two compactors follow the same compaction principle. The ICT is further described in Appendix C.

Resilient modulus was determined in the MATTA because it is now becoming an Australian standard test for the determination of bituminous pavement material properties such as resilient modulus. At the time of testing the draft Austroads Standard AUST-001 (1992) *Determination of the Resilient Modulus* was used. A description of the apparatus and test is given in Appendix C.

3.2.2 Materials

3.2.2.1 RAP

Reclaimed Asphalt Pavement (RAP) is defined by the Asphalt Institute (1984) as removed and/or processed pavement material containing asphalt (bitumen) and aggregate.

The RAP used in this study came from a variety of sources around Melbourne. The material was crushed to 20mm maximum size at the Concrete Recyclers' Laverton plant.

As the material came from different sources it is not known why it was removed, i.e. whether the pavement had any type of distress or if it was removed because the road was upgraded. The only information related to the state of the material was the viscosity of the bitumen, which was determined on a representative sample at the end of the testing program. The viscosity value indicated that the material had oxidised and pavements consisting of it could well have been showing distress.

Bitumen oxidises when the hydrocarbon particles are united with oxygen particles, and a portion of the hydrogen and carbon particles are eliminated producing an oxidised hydrocarbon (Hunter, 1994). Various chemical reactions occur during oxidation and the most common is:

$$C_xH_y + O \rightarrow C_xH_yO$$

For this reaction to occur, large amounts of activating energy in the form of heat and light are required. Oxidation can also occur in the absence of light, but it is considered to be a long term process in the hardening of bituminous binders. This oxidation occurs when oxygen enters from air contained in voids in the compacted pavement.

Bitumen is composed of asphaltene particles surrounded by resins which exist within the oil medium. As the resinous particles break down due to exposure to heat and oxygen in the atmosphere, some of the resinous particles, known as maltenes, become asphaltene chains and the remaining resinous particles evaporate, making the bitumen more viscous and stiff. This breakdown is known as oxidation and, according to Whiteoak (1990), the oxidation in a given time doubles for every 100°C rise in temperature.

If the oxidised asphalt is to be reused, it is necessary to bring it back to its original viscosity. To do so, binders that contain softening agents as well as the chemical particles lost in the oxidation process need to be added. These binders are called recycling agents or rejuvenators.

3.2.2.2 Rejuvenator

Rejuvenating agents are organic materials with chemical and physical characteristics which restore aged asphalt to desired specifications. The rejuvenator (or recycling agent) used in this investigation is a light oil with the trade name Cyclogen ME. It belongs to a family of maltene-based recycling agents. It was used in emulsion form, consisting of 35% water and 65% residue of various chemical compositions. These values were checked by testing the emulsion in accordance with AS 1160 Appendix D.

Whether the rejuvenator is applied as an emulsion or an oil depends on factors such as the condition of the RAP and the quantity of Cyclogen required. When RAP rejuvenators, such as Cyclogen, are applied as emulsions, they consist of two components - water, and a hydrocarbon chain with an affinity for bitumen and a structure with a surface charge either positive (cationic) or negative (anionic) which is attracted to water molecules. The rejuvenator softens the old binder when the water evaporates and leaves the hydrocarbon chain to combine with the oxidised bitumen. This separation of the water from the residue is known as the breaking action of the emulsion.

Hunter (1994) defines the breaking action of an emulsion as the coating of the surface of aggregate particles when the separation between the two elements (hydrocarbons and water) takes place. According to Hunter, the breaking action has two stages - named flocculation and coalescence. Flocculation is defined as the conglomeration of tiny bitumen drops around the surface of aggregate. Coalescence consists of the union of the individual particles to form a continuous film. In the case of RAP, emulsions used have solvents that soften the old binder and, in the coalescence stage, all the particles, old and new, are joined forming a uniform film of restored viscosity.

The breaking action is completed when coalescence occurs - in other words, when the water present in the material has evaporated. When this occurs, the broken emulsion acquires a cohesive strength.

In the United States and in Great Britain, the term 'breaking action of the emulsion' is often used by some authors. In this thesis, the term 'rejuvenating action' will be used.

CHAPTER 4 *TESTING PROCEDURE*

4.1 DESIGNED TESTING PROCEDURE

The testing procedure designed for this research, consisted of two phases. Phase One consisted of a series of tests used to determine the required rejuvenator content (new binder) to add to the RAP and the determination of a compaction density. This phase is later described in more detail.

Phase Two consisted of the determination of a curing temperature which will accelerate the rejuvenator, making it work faster with the old binder. To do so, three procedures were designed. Procedure One consisted of curing compacted RAP specimens at three different temperatures- 25°C, 60°C and 90°C. Procedures Two and Three consisted of curing specimens before compaction for 6 hours at 25°C and 60°C respectively and, after compaction curing at a temperature selected from Procedure One. This phase is also described later in this chapter. The following Table 4.1 depicts briefly each testing procedure.

	PROCEDURE ONE			PROCEDURE TWO	PROCEDURE THREE
	GROUP 1	GROUP 2	GROUP 3		
No. OF SPECIMENS	8	5	5	5	5
MIXING	Hand Mixing	Hand Mixing	Hand Mixing	Hand Mixing	Hand Mixing
LOOSE STORAGE	N/A	N/A	N/A	25°C for 6 hours.	60°C for 6 hours
COMPACTION	To a target density				
CURING	25°C	60°C	90°C	Selected Temp. from Procedure One	
TESTING	For resilient modulus				

Table 4.1 Brief description of testing Procedures.

4.2 VARIABLES AND CONSTANTS

A sample preparation procedure is an essential aspect of the mix design of asphalt pavements. The aim of sample preparation is to produce homogeneous laboratory specimens that will have properties similar to those of recycled material compacted in the field. In developing a laboratory procedure, effects of different factors on the properties of cold recycled asphalt must be investigated.

4.2.1 Constants

The factors which were kept constant were:

i) the type of rejuvenator (Cyclogen ME). Its selection as a constant was because the industry partner wished to only use this type;

ii) the percentage of rejuvenator added;

iii) the target density (or compaction density). The Maximum Dry Density was chosen because this is the density that is commonly specified for real pavements;

iv) the moisture content at the mixing stage. This would be the OMC since MDD was desired as the target density.

At the mixing stage the material was brought to the OMC. The target density was the MDD obtained under Modified compaction. The percentage of rejuvenator to be added depends on the grading and bitumen content of the RAP. Therefore, these factors were kept constant for all test specimens.

4.2.2 Variables

4.2.2.1 Curing Time

Curing time was selected as a variable because, as time increases, resilient modulus, moisture content, bulk density and viscosity of the bitumen in the RAP specimens change. Studies done by Epps (1990) and Tia *et al* (1983) showed that, as curing time increases, the modulus and viscosity of the binder in the RAP material increased. On the other hand, moisture content decreased and, after a few weeks, became constant.

In this study, the initial curing time was 24 hours between compaction and testing, and after the first test the specimens were kept in the curing environment and were subsequently tested at approximately 3, 7, 14, 28, 60, and 116 days after compaction. A loose storage time was also used, and could be considered as part of the curing process. This loose storage consisted of a six hour period before compaction.

4.2.2.2 Curing Temperature

Curing temperature was selected as a variable in order to observe the effect of different temperatures on the increase in resilient modulus. For the study, three different curing temperatures of 25°C (defined as room temperature), 60°C and 90°C were selected.

Room temperature was chosen because this is the temperature at which most laboratories are kept and also because it is thought to be similar to the temperature at which most road pavements are compacted and cured. 60°C was chosen because, at this temperature, the curing process can be accelerated without oxidising the rejuvenated RAP and because it would simulate the curing of a pavement throughout its service life (Tia *et al*, 1983). Also, this temperature can be observed in pavements during hot summer days.

The curing at 90°C was chosen to find out whether, at a further elevated temperature, the curing process would be accelerated, thus reducing both the laboratory time and the delay in obtaining data. However, it was thought that this temperature might also affect the rejuvenated RAP by destroying the rejuvenator and reversing the process into oxidation, but it was not known how long this would take to occur.

Room temperature (25°C) and 60°C were used for loose storage. Specimens were placed in open trays before compaction. The loose storage was done in order to observe whether the extra curing time at different temperatures before compaction would affect the modulus result.

4.3 TESTING PROCEDURE PHASE ONE

The aim of Phase One was to determine both the required binder (rejuvenator) content and the target density of the reclaimed asphalt to be used. It was decided that the MDD be used as the target density. The laboratory tests performed included: particle size distribution of both RAP and clean aggregate, bitumen extraction, OMC/dry density and initial moisture content. The grading of the clean aggregate and the bitumen content are needed for the calculation of the binder content. Figure 4.1 depicts the order in which the tests were done.

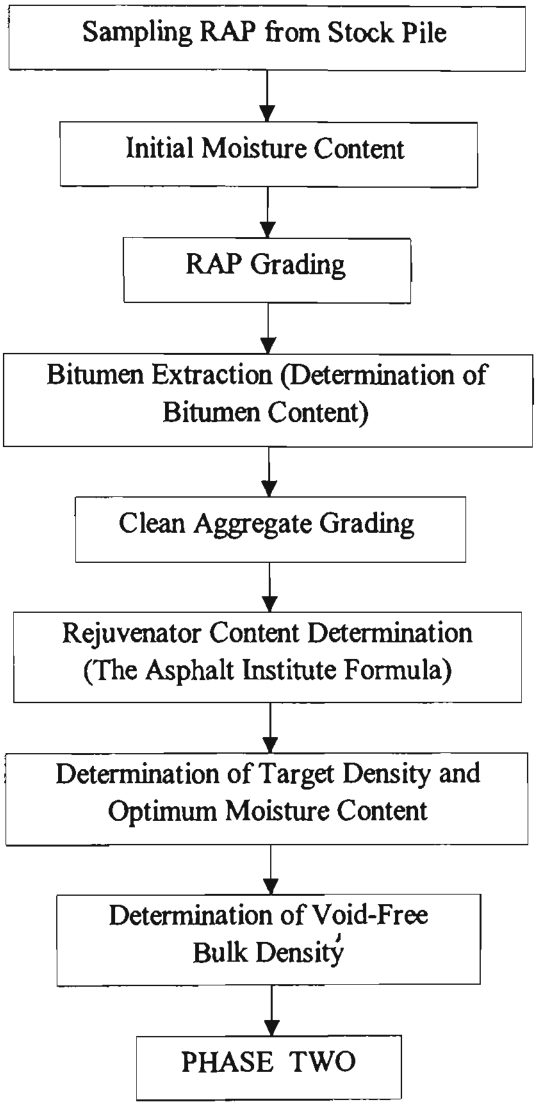

Figure 4.1 Steps followed in Phase One

4.3.1 Sampling and Crushing

RAP material was crushed and sampled at the Concrete Recyclers Pty. Ltd. plant at Laverton. The crushing process is described in Appendix C.

All sampling was carried out in accordance with AS 1141.3 (1986). A front-end-loader was used following the guidelines stated in section 6.1.10.5 *Sampling aided by power equipment.* The sampled material was later reduced to sub-samples in accordance with section 6.1.5.3 *Reduction by quartering.*

4.3.2 Initial Moisture Content (IMC)

Initial Moisture Content (IMC) is defined as the amount of moisture present in the RAP at the time of sampling. Prior to sampling moisture was added to the RAP during the crushing process to reduce the loss of fines. IMC is thus the ratio of weight of water in the sample after crushing to weight of solids and it was determined in accordance with AS 1289.B1.1 (1977).

4.3.3 RAP Grading

The particle size grading of the RAP material was evaluated by means of a sieve analysis, done in accordance with AS 1141.11 (1980). The grading of RAP was done to compare it with the grading of the clean aggregate (i.e. the aggregate after bitumen removal) to see how much they differ from one another and if the RAP grading would meet the required mix design guidelines for pavement materials.

4.3.4 Bitumen Extraction

Extraction of bitumen from RAP to determine the bitumen content was done in accordance with AS 2891.3.3 (1991), except for placing the filter aid on the filter pad rather than in the 2L flask. Weighing errors can occur if the filter aid sticks to the walls of the flask.

The bitumen content was obtained in order to find the percentage of the old binder or bitumen still attached to the RAP. The bitumen content of the RAP was determined on the basis of the relative weights of the extracted bitumen and the clean oven-dried aggregate as stated in AS 2891.3.3 (1991) sections 8.2.1a, 8.2 and 8.3. This determination was necessary to estimate the required amount of rejuvenator to be added to the RAP.

4.3.5 Clean Aggregate Grading

Aggregate grading is a prerequisite for the design of bituminous mixes. The grading of the washed aggregate was used to calculate the asphalt demand, or amount of rejuvenator to add. Sieving was performed after the washed aggregate was dried in an oven for 24 hours at a temperature of 105°C and then left to cool.

4.3.6 Rejuvenator Content

The required binder (rejuvenator) content was calculated following the Asphalt Institute formula. This formula was chosen because it is easy to understand, does not require the data from tests other than grading and bitumen content, is commonly used by many organisation, and is simple to use. The term bitumen used in this thesis is synonymous with the term asphalt used in the Asphalt Cold Mix Manual (1983). The estimation of the amount of rejuvenator requires the bitumen content of the RAP and the grading of the clean aggregate, and involves three steps which are described as follows:

i) Percent Bitumen Demand of the Clean Aggregate[1] (P_C).

The rejuvenator demand (or binder demand) required by the aggregate in the sample was calculated as follows:

$$P_C = 0.035a + 0.045b + Kc + F \qquad (4.1)$$

where:

P_C = Percentage of required binder by weight of total mix

a = Percentage of mineral aggregate retained on 2.36mm sieve

b = Percentage of mineral aggregate passing 2.36mm sieve and retained on 75μm sieve

c = Percentage of mineral aggregate passing 75μm sieve

K = 0.15 for 11-15 percent passing 75μm sieve

0.18 for 6-10 percent passing 75μm sieve

0.20 for 5 percent or less passing 75μm sieve

F = 0.85 percent.

The Asphalt Institute suggests the use of between 0 and 2 percent for F depending on the likely amount of binder which could be absorbed by the aggregate. The value is based on an average specific gravity of 2.60 to 2.70. When data is not available, a value of between 0.7 and 1.0 should be used. In this research a mean value of 0.85 was used because no data was available.

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[1] The Asphalt Institute uses the words Combined Aggregate rather than Clean Aggregate in cases where virgin aggregate is added to the RAP.

ii) Percent of New Bitumen in Mix (P_r).

The quantity of rejuvenator to be added to the RAP was calculated by subtracting the bitumen content from the calculated binder (rejuvenator) demand, as follows:

$$P_r = P_c - \left(P_a \times P_p\right) \qquad (4.2)$$

where:

P_r = Percentage of rejuvenator to be added to the recycled mix

P_c = Percentage of required binder by weight of total mix

P_a = Percentage bitumen content of RAP

P_p = Percentage of reclaimed asphalt pavement in the recycled mix.

When 100% RAP is used equation 4.2 can be reduced to:

$$P_r = P_c - P_a \qquad (4.3)$$

iii) Total Percent of Rejuvenator to Add to RAP

The total amount of rejuvenator added to the RAP as an emulsion was calculated by dividing P_r by the fraction by weight of the residue in the emulsion (which was 0.65 in this case, as the emulsion used consisted of 65% residue and 35% water -percentages checked in accordance with AS 1160 Appendix D).

$$P_b = \frac{P_r}{65} \times 100 \qquad (4.4)$$

where:

P_b = Percentage by weight of emulsified rejuvenator.

4.3.7 Optimum Moisture Content (OMC)

The OMC was required in order to determine the quantity of water to be added to the RAP specimens prior to compaction, so that the target density (MDD) can be achieved in the minimum time in the gyratory compactor. If too little water is added the number of cycles to achieve MDD will be excessive. If too much water is added, the MDD may not be achieved.

The relationship between dry density and moisture content of RAP was determined in accordance with AS 1289.E2.1 (1977) and the Vic Roads Test Method RC 315.01 (1991). A modified compactive effort of 2703kJ/m^3 was applied by means of a mechanical apparatus complying with the specification stated in note 1 of AS 1289.E2.1 and note 2 of the Vic Roads method. RC 315.01 and AS 1289.E2.1 state the same testing procedure, with the only difference between them being that RC 315.01 describes 3 different types of moulds to be used for compaction. Different moulds are used depending on the size of aggregate in the mix. In this research, mould A was used because most of the particles in the mix passed the 19.0mm sieve. Its dimensions are 105mm internal diameter and 115.5mm height.

4.3.8 Void-Free Bulk Density

The void-free bulk density of the RAP was determined in accordance with Vic Roads Test Method CRB 202.01 (1976). The void-free bulk density is the same as the average specific gravity of the bitumen-coated particles. The scope of the method is given as follows: "*Void Free Bulk Density of Asphalt (After Rice)* is used to determine the bulk density of a theoretically voidless asphalt in order that the percentage of air voids in a compacted asphalt specimen may be determined. It depends for its validity on the assumption that every particle in the dispersed asphalt is surrounded by a bitumen film through which no water can penetrate". The results obtained from this test together with the calculated bulk density at OMC were used to determine the percentage voids of the compacted specimens. The test is described in Appendix C.

4.4 TESTING PROCEDURE PHASE TWO

Phase Two consisted of determining a curing temperature which would make the rejuvenator work faster without oxidising the bitumen. This temperature was to be selected after consideration of the results obtained in the resilient modulus tests. Figure 4.2 shows the steps followed in this phase.

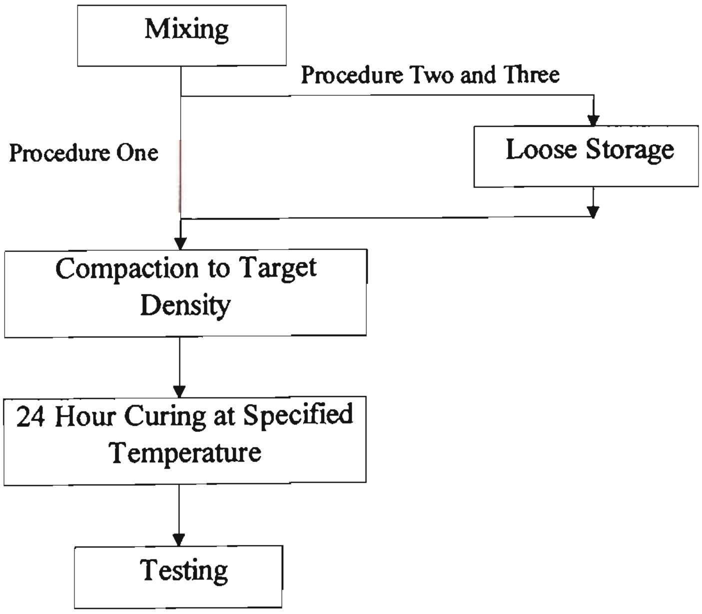

Figure 4.2 Steps followed in Phase Two.

The three testing procedures in this phase differed from one another in the curing temperatures used, and a period of loose storage before compaction. The curing temperatures were 25°C, 60°C and 90°C. The loose storage periods were 6 hours at 25°C and 60°C. The procedures were similar as regards mixing, compaction, curing time and testing.

4.4.1 Mixing Process And Mass Calculation

The mass of a specimen of approximately 1.5kg of the RAP material at Initial Moisture Content (IMC), was recorded and used to calculate the dry mass of the material as follows:

$$m_D = \frac{m_S}{100 + IMC} \times 100 \qquad (4.6)$$

where:

m_D = dry mass

m_S = mass of sample at IMC.

Once the dry mass was calculated, the Additional Mass of Water (AMW) required to meet OMC was calculated, as well as the amount of rejuvenator to be added.

$$AMW = \frac{m_D \times (OMC - IMC)}{100} \qquad (4.7)$$

The total amount of rejuvenator to add was calculated using the Asphalt Institute formula for cold recycling of asphalt as described in section 4.3.6. From this the mass of rejuvenator (as emulsion) M_{RE} to add was calculated as follows:

$$M_{RE} = \frac{m_D \times P_b}{100} \qquad (4.8)$$

where:

P_b = Percentage by weight of emulsified rejuvenator.

The actual mass of water to be added to the specimens at the same time as adding the rejuvenator was:

$$\text{mass of water} = AMW - (0.35 \times M_{RE})$$

This is because the amount of water present in the emulsion is 35%.

4.4.2 Compaction Process

All specimens were compacted to a calculated wet density using a gyratory compactor. The reasons for selecting this type of compactor over other types (e.g. kneading, Marshall, AshPac), were:

i) The compaction action can be continued until the specimen thickness is reached which gives the required density and air voids.

ii) The compaction action orients the particles in a way which is similar to that of field compaction equipment and should, therefore, produce test specimens with properties similar to field cores.

In addition, the machine is easy and straightforward to operate, can be automated, is comparatively quiet, can be used on site, and is considered environmental friendly (Kadar, 1992). The particular machine used for these tests was an Intensive Compaction Testing (ICT) machine.

Caltabiano and Walters (1991) showed that the ICT gyratory compactor produced specimens with higher modulus values than other compactive equipment (Marshal, AshPac, kneading) and these were close to values obtained from pavement cores.

4.4.2.1 ICT Gyratory Compactor

The process which the ICT follows when compacting specimens is called shear compaction. Under a constant normal stress a shearing movement is applied, which brings the particles close together. The normal stress is applied to the material by compressing it in a cylinder between top and bottom plates. The required shear is created by the gyratory movement of the cylinder during the test. It produces cylindrical specimens of 65 - 100mm in height and 100mm in diameter. The apparatus compacts specimens under constant pressure, constant speed and a fixed gyratory angle, which can be selected to meet specifications (Kadar, 1992). Figure 4.3 depicts the compacting action of the ICT apparatus.

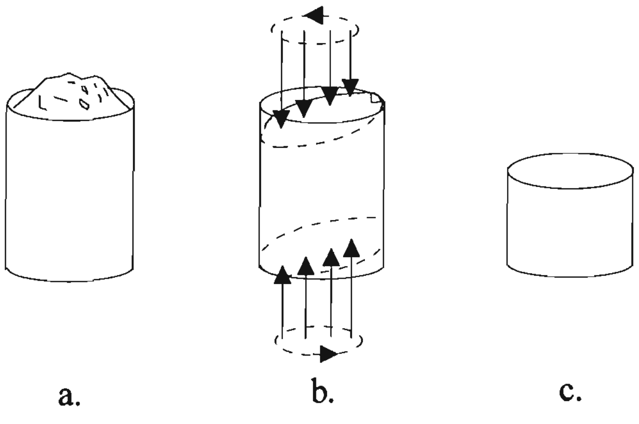

Figure 4.3 ICT gyratory action.

a. Cylindrical mould with specimen material to compact.
b. Specimen being compacted using gyratory motion with pressure being applied to both plates
c. Compacted specimen.

4.4.2.2 Compaction Test Procedure

The compaction of specimens commenced once a sample of RAP was mixed with the required amount of water and rejuvenator. The compaction test procedure is described in Appendix C and the compaction curves produced from the test are shown in Appendix G.

4.4.3 Curing Time

All specimens were cured at the chosen temperatures for 24 hours after compaction, prior to the first resilient modulus determination. One specimen required 48 hours curing before testing because it was too weak to be tested after 24 hours.

After the 24 hour curing period and the testing, all specimens were further cured and tested at increasing periods of time, that is, after 3, 7, 14, 28, 56, and 112 days. This was done in order to find out what increase in modulus occurred with time after compaction, at both room temperature and elevated temperatures.

4.4.4 Modulus Testing

All specimens were tested on the MATerial Testing Apparatus (MATTA) using the diametral loading Indirect Tensile Test (ITT) to determine the Resilient Modulus of the RAP specimens. The MATTA was used for the testing because:

i) It has been recommended by the Australian Pavement Research Group (APRG) (Sharp and Alderson (1991)) for testing bituminous mixes to provide parameters for the mechanistic design of pavements.

ii) It can be used in a non-destructive way, so that specimens can be re-tested at subsequent times.

4.4.4.1 Apparatus Description

The MATTA is based on a simple reaction frame which consists of a stainless steel base plate, two vertical columns supporting a crosshead, two loading strips, a testing yoke, an air cylinder, a source of compressed air, a solenoid valve system and transducers. The two vertical columns are threaded to allow for height adjustments of the crosshead beam to be made. Figure 4.4 depicts the MATTA apparatus used to determine resilient modulus of RAP specimens.

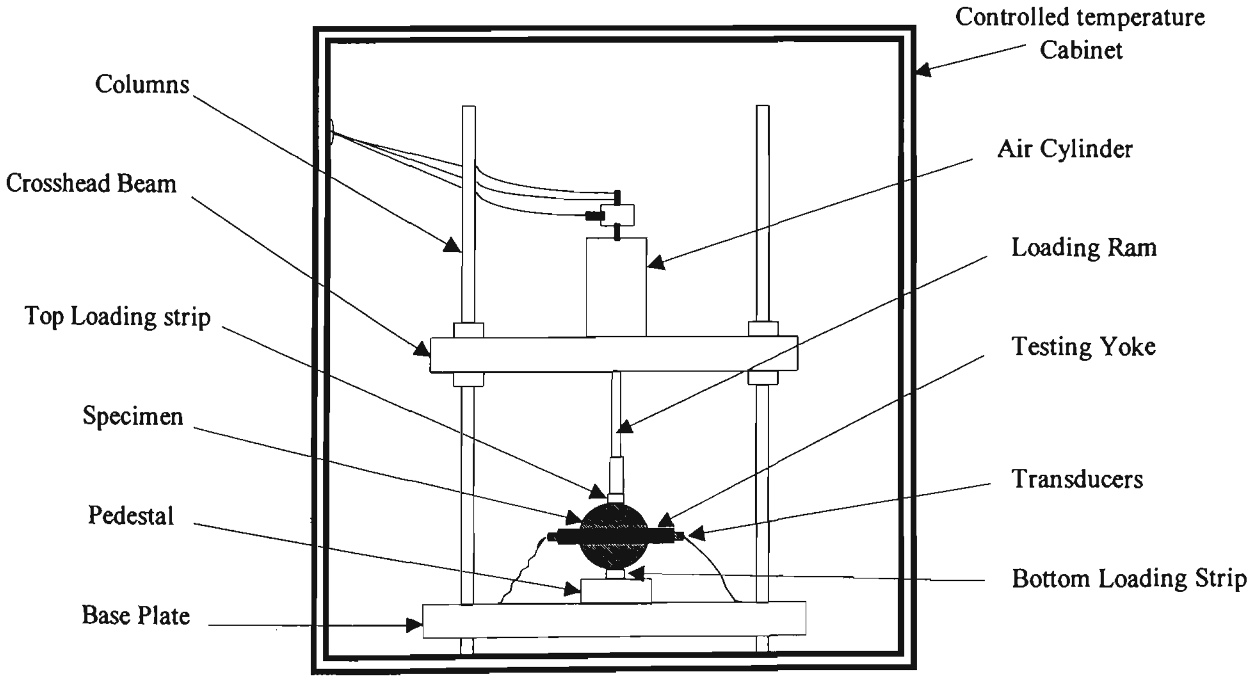

Figure 4.4 MATTA apparatus.

Dynamic compressive forces are applied by means of a compressed air source connected to an air cylinder through an electronically-activated solenoid valve system which controls the air supply. The air cylinder is mounted on the crosshead. The solenoid valve allows a pulse of compressed air to pass through the air cylinder, creating a pulsed load on the specimen. For testing bituminous materials the apparatus is placed in a temperature-controlled cabinet.

4.4.4.2 Indirect Tensile Test (ITT)

The ITT (also called Repeated Load Tensile Test (RLTT)) is performed on Marshall-sized test specimens. Alderson (1992) states that "Marshall-sized specimens are ideal, as these do not require excessive loads to produce significant horizontal deformation". Resilient modulus can be determined on laboratory specimens and on cores taken from laboratory-produced slabs or from road pavements. For the resilient modulus test the cylindrical specimen is placed on its side and loaded vertically across its diameter.

A pedestal on the base plate supports a stainless steel loading platen (or loading strip) which supports the specimen. A second loading strip which distributes the compressive load uniformly is placed on top of the specimen.

The two loading strips each have a concave surface with radius of curvature equal to that of the nominal 100mm diameter specimen. This holds the specimen in place and stops it from moving sideways while being tested. The outer edges of the curved surface are smoothed to remove sharp edges which might cut or split the specimens while testing. The top strip is held in place by two rods which are attached to the testing yoke, forming a small frame.

The testing yoke is placed around the specimen. It holds the Linear Variable Displacement Transducers (LVDT) which touch the specimens by means of disc-ended probes. Two LVDTs are located on the testing yoke, one on each side in line with the horizontal diameter of the specimen, to measure the lateral deformation produced by the load pulse.

The ITT involves the loading of cylindrical specimens with repeated loads acting parallel to and along the vertical diametrical plane. The compressive load produces a relatively uniform indirect horizontal tensile stress which is perpendicular to the applied load, as depicted in Figure 4.5.

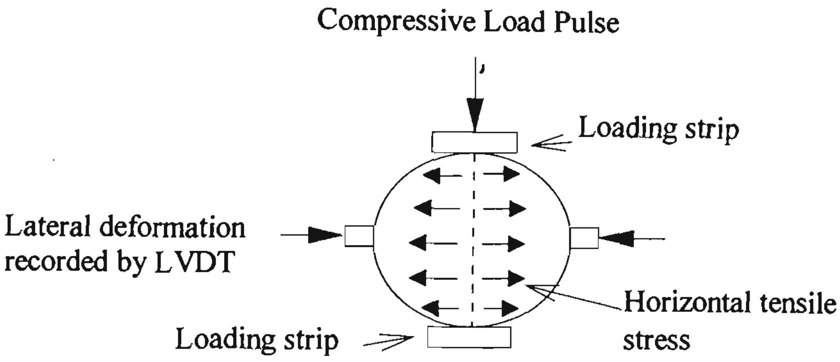

Figure 4.5 Test sample under compressive loading (ITT).

The testing was done in accordance with the draft Austroads Standard AUST-001 (1992). A description of the test is given in Appendix C.

4.4.4.3 Resilient Modulus

Resilient modulus is a measure of the elastic stiffness of asphalt mixes and is considered one of the most important characteristics of a pavement material

(Epps *et al*, 1978). It is the ratio of the applied stress to the recoverable strain when a dynamic load is applied. In the indirect tension mode resilient modulus is calculated from:

$$M_R = \frac{P(\nu + 0.27)}{H \times t} \tag{4.9}$$

where:

M_R = resilient modulus (MPa)
P = applied Load (N)
ν = Poisson's ratio (assumed value)
H = Total recoverable horizontal deformation (mm)
t = specimen thickness (mm)
0.27 = a constant (from Austroads-001).

A value of 0.4 was assumed for ν in the testing done for this project.

4.4.5 Preparation Procedure

As stated in sections 4.1 and 4.4, three procedures were proposed for the preparation and testing of RAP specimens. Each procedure is described below.

4.4.5.1 Procedure One

The aim of Procedure One was to select a temperature at which to cure RAP specimens in order to accelerate the rejuvenator action and therefore obtain the highest resilient modulus after 24 hours. At higher temperatures, water evaporates more quickly and the chemical reaction is accelerated between the rejuvenator and the RAP. However, once the temperature reaches a certain level the bitumen will start to oxidise, and it was desired to avoid this. The selected temperature would later be used in Procedures Two and Three. The steps followed in this procedure are depicted in Figure 4.6.

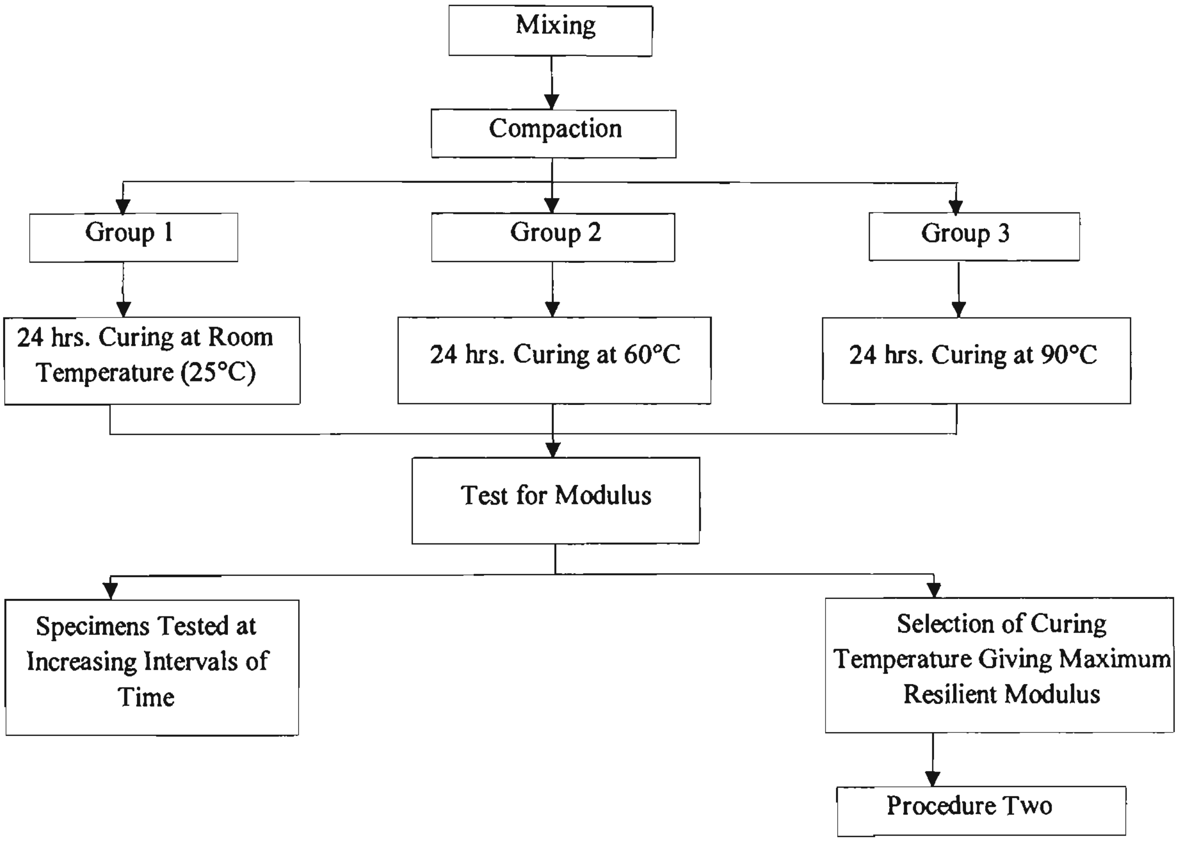

Figure 4.6 Steps followed in Procedure One.

As shown in Figure 4.6, the test specimens used in Procedure One were divided into three groups. A different curing temperature was used for each group, these being room temperature (25°C), 60°C and 90°C for Groups 1, 2 and 3 respectively.

Eighteen specimens were used and were divided into groups which contained eight in Group 1 and five in each of Group 2 and Group 3. The minimum number of asphaltic mix specimens usually tested on the MATTA is three and the results are averaged. In this study five specimens were used in Groups 2 and 3 to allow for possible breakage of specimens when being handled. Eight specimens were prepared for Group 1 because, after 24 hours curing at room temperature, the specimens are generally not strong enough to withstand the testing procedure without producing excessive deformation or breakage when handled, so that some spare specimens were prepared for use if necessary.

The initial steps depicted in Figure 4.6 (mixing, compaction, curing time and testing) were discussed in sections 4.4.1, 4.4.2, 4.4.3 and 4.4.4, since these were used in each procedure. The results obtained from the testing of each group were averaged and the temperature that produced the highest resilient modulus was selected and was later used in Procedures Two and Three. Once the testing was completed, all specimens were returned to their respective curing environments and were further cured for increasing intervals of time. At the end of each time interval, specimens were tested to observe the effect of curing time and temperature on the modulus.

4.4.5.2 Procedure Two

The aim of this procedure was to determine whether a storage period at a selected temperature before compaction had an effect on the modulus. It was expected that the modulus would increase because the extra storing period should allow the rejuvenator action to take place. The storage temperature chosen was room temperature (25°C). The steps followed in this procedure are depicted in the following flow chart in Figure 4.7.

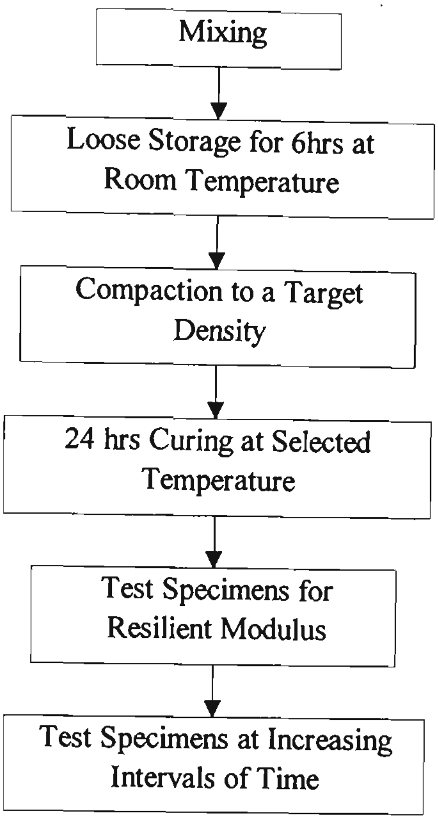

Figure 4.7 Steps followed in Procedure Two.

All the steps shown in Figure 4.7, except one, were discussed earlier in this chapter since these were used in each procedure (mixing, compaction, curing time and testing). The only difference in this procedure was that of the loose storage period and temperature.

At the end of the testing, it was decided that all specimens would be further cured and tested at increasing intervals of time to observe how the curing temperature affected the modulus. Five specimens were used in this procedure. The choice was made for the same reasons given in section 4.4.5.1.

4.4.5.3 Procedure Three

Procedure Three followed exactly that of Procedure Two except that the loose storage took place at 60°C. This temperature was chosen to accelerate the breaking of the emulsion. Figure 4.8 depicts the steps followed in Procedure Three.

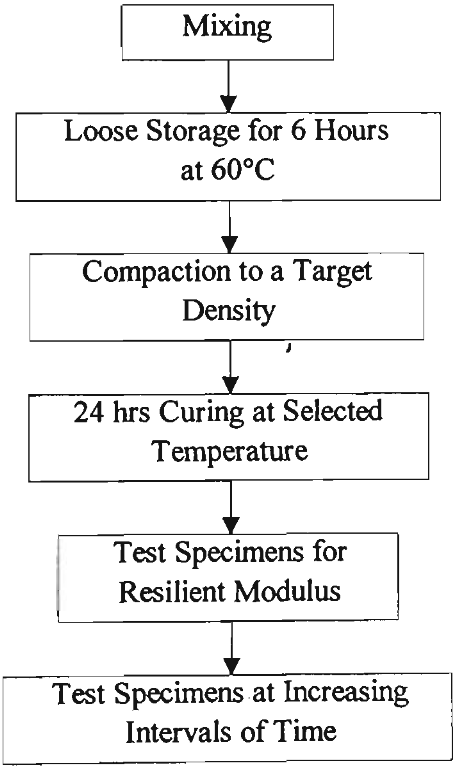

Figure 4.8 **Steps followed in Procedure Three.**

Once the specimens were tested after 24 hours curing, specimens were continuously cured and tested at increasing intervals of time as in Procedure One. This was done to observe how modulus was affected. Five specimens were used in this procedure.

4.5 VISCOSITY OF BITUMEN IN RAP

The viscosity test was done to find out the effect of the rejuvenator as the specimens were cured and to determine what effect viscosity has on the modulus. It was intended that viscosity testing would be done throughout the testing, but because of the expense involved it was only done at the end of the program. Instead of viscosity tests, it was hoped that the viscosity could be estimated from phase angle measurements made during modulus testing. However, this did not give meaningful results, and conventional viscosity testing was required. The viscosity of RAP specimens was then determined at the end of modulus testing by means of the sliding plate micro-viscometer in accordance with AS 2341.5 (1986).

4.5.1 Phase Angle

Viscosity was calculated by determining the phase angle, which can be obtained from the data stored in the MATTA for tested specimens. The phase angle (ϕ) is defined as the time difference between the material response (or displacement) and the load application (or force) when specimens are tested at the same frequency or loading cycle. It is calculated by plotting force and displacement against load-time cycle. The difference or delay between the crests of the force and displacement curves is called phase angle (Dickinson (1983)). Figure 4.9 depicts this phenomenon:

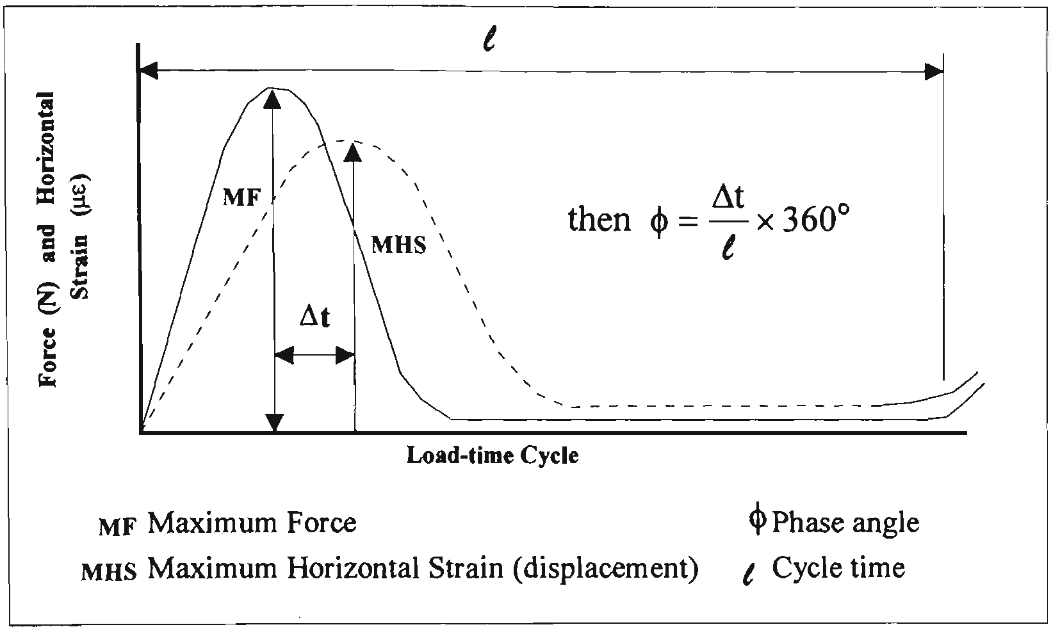

Figure 4.9 Determination of phase angle.

The phase angle can have any value between 0° and 90°. If it is 0°, the material deformation is purely elastic, and if 90° the response is purely viscous (Molenaar *et al*, 1992). The phase angle was calculated using the data obtained from the resilient modulus testing by plotting the applied force and the corresponding horizontal strain against the loading cycle. The loading cycle is the period of the waveform which was 3 seconds. The phase angle was then obtained by measuring the difference between crests/peaks (Δt) of the two waveforms and, dividing them by the period of the waveform (ℓ), this ratio was multiplied by 360° to give the phase angle.

The determination of viscosity by means of the phase angle was abandoned because the results were difficult to obtain and no difference in angle was observed between procedures, which indicated that the apparatus was not sensitive enough to calculate the phase angle from the results obtained from modulus testing.

4.5.2 The 'Shell' Sliding Plate Micro-viscometer

The determination of the apparent viscosity by mean of the 'Shell' sliding plate micro-viscometer was performed at the Vic Roads laboratory. Ten specimens were tested, of which one was RAP material prior to adding rejuvenating agent and nine were compacted specimens which had rejuvenating agent added. The selection of specimens for testing is described in section 5.3.

To determine the apparent viscosity of the bitumen in the RAP, the procedure in AS 2341.5 (1986) was followed. Prior to the commencement of the test, the bitumen was recovered from the RAP. This was done in accordance with Vic Roads test method CRB 212.01 (1981). The test temperature used was 45°C as indicated in AS 2341.5 (1986). The steps followed in the determination of the viscosity of bitumen in RAP are presented in Appendix C.

CHAPTER 5 *TEST RESULTS*

5.1 PHASE ONE RESULTS

The object of Phase One was the determination of the required rejuvenator content and the maximum dry density of RAP.

5.1.1 Initial Moisture Content

A sample of stockpiled material of approximately 60kg was split into 1.5kg sub-samples. Five of these were selected ,at random for determination of IMC, grading and bitumen content. Initial moisture content for all five specimens was 3.2%. Numerical results obtained for each specimen are presented in Appendix D.

5.1.2 Grading

The clean aggregate grading was required in order to determine the amount of rejuvenator to be added and also to determine if the grading was in accordance with Vic Roads Standard Specifications for Road Works Section 407Q Mix Design Requirements for Hot Asphalt Mixes.

A well-graded material allows the fitting of smaller particles into the voids created by the large particles, producing in this way a denser material when compacted. Vic Roads mix design requirements limit the percentage fines, because too many fines reduces the contact between larger particles and also results in excessive demand for rejuvenator. If this occurs, the stiffness and strength of the material when compacted will be reduced.

The RAP grading was obtained to find out the degree of binding of particles together by the bitumen, and to compare the shapes of the two grading curves. From Figure 5.1 can be observed that the clean curve shows a large increase in the percentage passing from the 6.70mm to the 75μm sieves, compared to the RAP curve where more particles were retained in these sieves (more clumping of particles were observed). For example, for clean aggregate an average of 77.8% passed the 6.70mm sieve and 8.92% passed the 75μm sieve, while for RAP, an average of 63.1% passed the 6.70mm sieve and 0.38% passed the 75μm sieve.

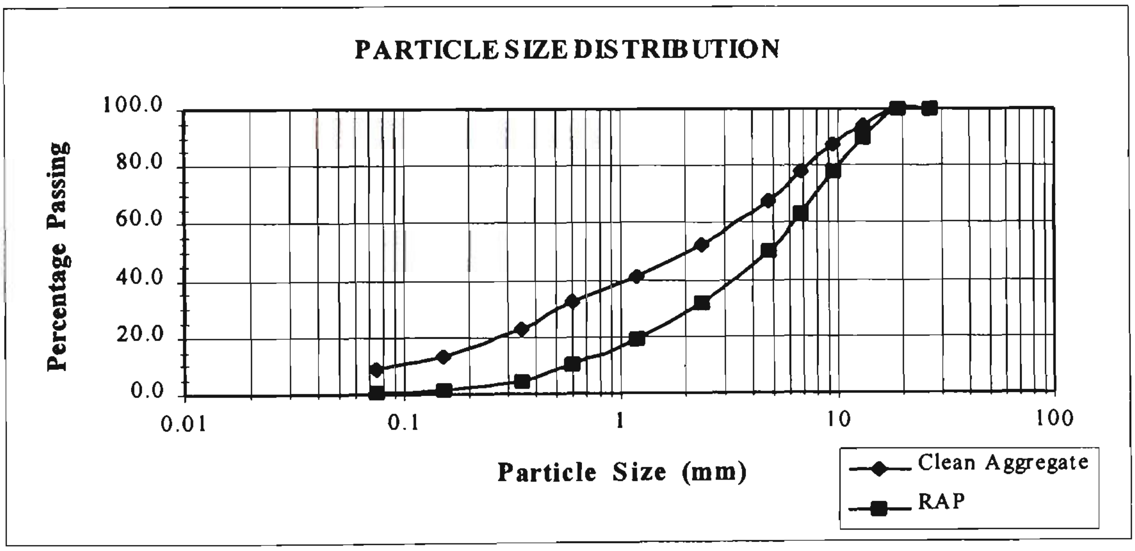

Figure 5.1 Average particle size distribution for clean aggregate and RAP.

5.1.2.1 Clean Aggregate Grading

Grading of the clean aggregate is shown in Figure 5.2. The grading represents the percentages passing at each sieve size for the five specimens used. It can be observed that there was little difference between any of the curves. The numerical values are given in Appendix D.

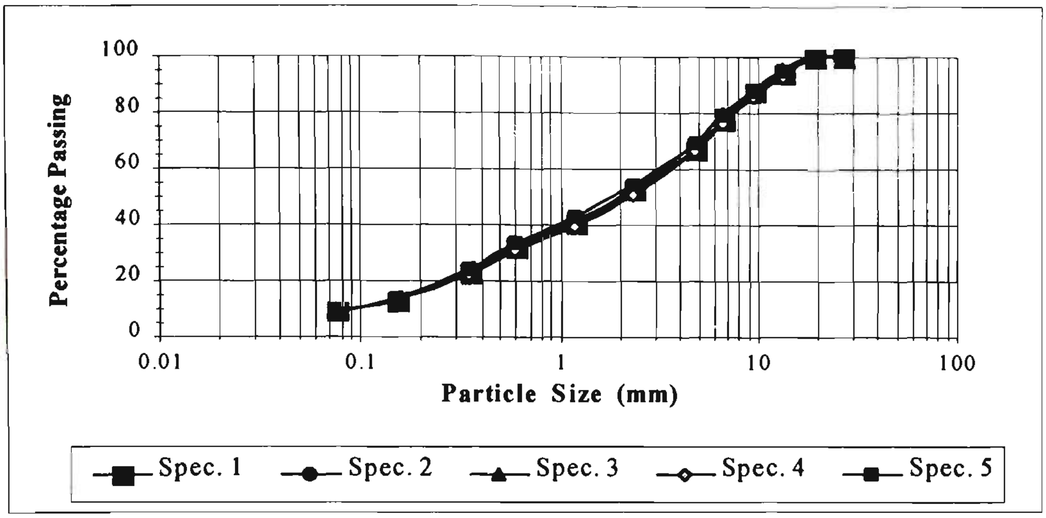

Figure 5.2 Particle size distribution of clean aggregate.

5.1.2.2 RAP Grading

Figure 5.3 shows the percentage passing at each sieve size for the five specimens used. Again, there was very little difference between the results obtained for each curve. The numerical values obtained are given in Appendix D.

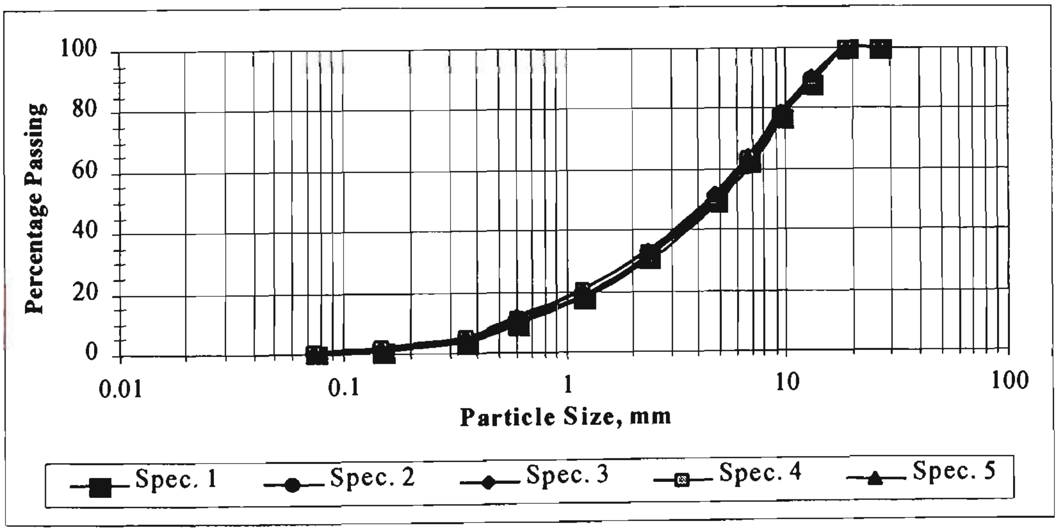

Figure 5.3 Particle size distribution of RAP.

5.1.3 Bitumen Content

The average bitumen content of the five specimens was 4.6%, with values ranging from 4.3% to 4.8%. According to Vic Roads mix design requirements, the usual bitumen content for a 20mm mix ranges from 4.0% to 6.5%. Allowing for the evaporation of volatile oils, this seems to indicate that the original bitumen content for the RAP would have been within this range. The results obtained for each of the five specimens tested are given in Appendix E.

5.1.4 Rejuvenator Content

The rejuvenator content calculated from the Asphalt Institute formula ranged from 1.3% to 1.7%, with an average value of 1.5%. The rejuvenator used in this study was supplied as an emulsion in which 65% was residue and 35% water. When applied as an emulsion, the average rejuvenator content then became 2.3%. Appendix E shows the calculation of the rejuvenator content and the values obtained for each specimen.

5.1.5. Maximum Dry Density and Optimum Moisture Content

The results of a modified compaction test using five specimens of RAP are shown in Table 5.1.

Specimen No.	Wet Density (kg/m^3)	Moisture Content %	Dry Density (kg/m^3)
1	2.116	5.3	2009
2	2.150	6.1	2026
3	2.180	7.0	2037
4	2.200	7.8	2041
5	2.188	9.3	2002

Table 5.1 Results obtained from dynamic compaction test to AS 1289.5.2.1.

Figure 5.4 is the resulting compaction curve, showing maximum dry density and OMC. From this Figure can be observed that the maximum dry density is 2044kg/m^3 at an OMC of 7.5%.

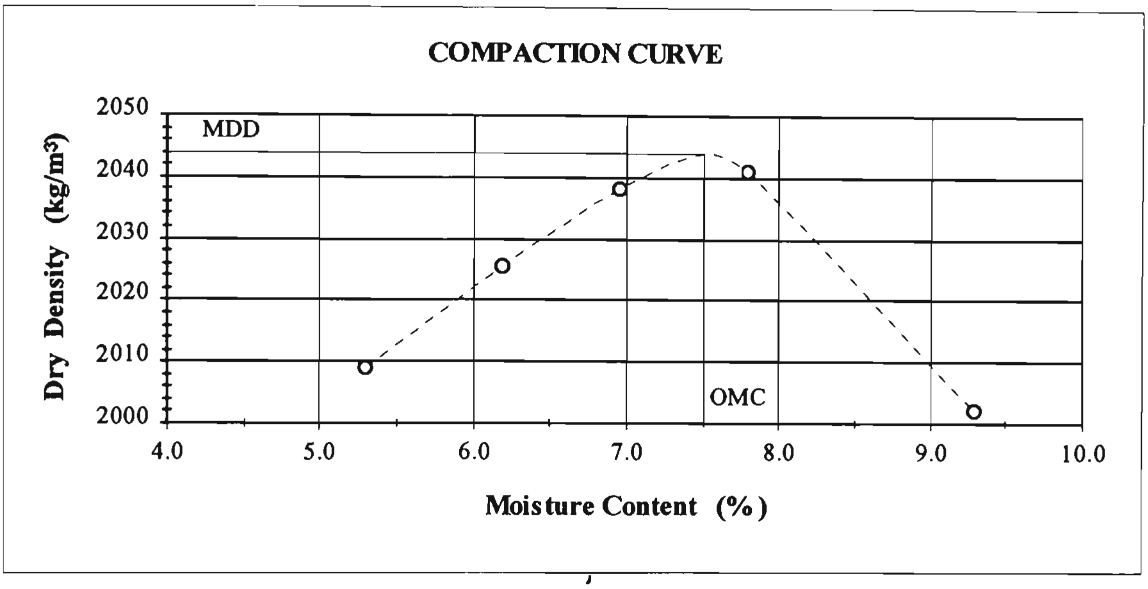

Figure 5.4 Dry density versus moisture content to determine OMC/MDD.

5.1.6 Void-Free Bulk Density - Void Contents

The Void Free Bulk Density (VFBD) was determined from two samples producing an average VFBD of 2438kg/cm^3 (2427kg/cm^3 and 2449kg/cm^3). This value was used to calculate the percentage voids of compacted specimens at the target density. The percentage voids was calculated using the following equation:

$$\text{Percentage Voids} = \frac{\text{VFBD} - \rho_B}{\text{VFBD}} \times 100$$

where:

ρ_B = Bulk density of compacted specimen

The bulk density of the compacted specimen was obtained from the modified compaction test to determine MDD. The bulk density was found to be equal to 2197kg/m^3 giving a percentage voids equal to 10.0%.

The change in percentage voids for all the specimens tested in each procedure are presented in Appendix F. These percentages were calculated from the bulk density of each specimen and the VFBD previously obtained. It was observed that the percentage voids changed throughout curing time from about 12% before curing to 17-18%. The following Table 5.2 shows the average percentage voids for each Procedure. The individual result for each specimen is presented in Appendix E.

PROCEDURE ONE						PROCEDURE TWO		PROCEDURE THREE	
GROUP 1		GROUP 2		GROUP 3					
Time (Days)	% voids	Time (Days)	% voids	Time (Days)	% voids	Time (Days)	% voids	Time (Days)	% voids
0	12.1	0	12.2	0	12.1	0	12.3	0	11.5
-	-	1	17.0	1	17.6	1	16.3	1	16.8
2	16.3	4	17.7	3	17.7	-	-	-	-
5	17.1	8	17.7	7	18.0	8	16.5	7	17.3
13	17.7	15	17.8	14	17.9	22	16.5	22	17.3
28	17.8	30	17.7	28	17.9	50	16.5	50	17.4
57	17.9	57	17.8	57	17.9	98	16.4	84	17.3
117	17.8	113	17.8	118	17.9	106	16.5	106	17.4

Table 5.2 Average percentage voids for specimens in Procedures One, Two and Three.

5.2 PHASE TWO RESULTS

Phase Two aimed at the selection of a post-compaction curing temperature that would accelerate the reaction between the rejuvenator and the RAP. This was to be decided after the determination of the effect on the modulus of curing specimens at different temperatures.

For resilient modulus determination, all specimens were tested at 25°C. Specimens cured at higher temperatures were allowed to cool for a period of at least 4 hours to reach the testing temperature. The curing temperature was selected after all specimens from each group in Procedure One were tested for modulus.

5.2.1 Procedure One

In Procedure One, specimens were compacted directly after mixing and cured for 24 hours before modulus testing. Three groups of specimens were cured-one at 25°C (Group 1), one at 60°C (Group 2) and one at 90°C (Group 3).

Specimens were then further cured at the same temperatures and retested for modulus to observe the change in modulus with time. An experimental investigation reported by Santucci and Hayashida (1983) indicated that modulus increases rapidly during the early curing period. This phenomenon is due to the breaking action of the rejuvenating agents. After addition of rejuvenator, the water in the emulsion gradually evaporates leaving the residue to act on the bitumen binder.

5.2.1.1 Group 1

Group 1 specimens were cured at room temperature (25°C) for 24 hours before being tested for modulus. Specimens were returned to the curing environment and tested at increasing intervals of time. The average results obtained are shown in Table 5.3, and the numerical results obtained for each specimen are given in Appendix H1.

TIME ELAPSED (Days)	AVERAGE SPECIMEN MASS (g)	AVERAGE APPLIED FORCE (N)	AVERAGE HORIZONTAL STRAIN ($\mu\varepsilon$)	AVERAGE RESILIENT MODULUS (MPa)	AVERAGE BULK DENSITY (kg/m^3)	No. OF SPECIMENS
0	1120.0	-	-	-	2141.9	8
2	1069.1	412	327.5	130	2040.8	1
5	1060.1	408	172.7	241	2020.6	1
13	1048.3	422	82.9	515	2007.1	1
28	1050.0	412	81.9	513	2004.4	5
57	1048.2	393	75.8	520	2002.4	6
117	1048.9	392	74.9	533	2003.3	6

Table 5.3 Average test results obtained for specimens cured at room temperature (Procedure One, Group 1).

The specimens from this group could not be tested after only 24 hours curing because at 25°C the evaporation of water and therefore the rejuvenating action takes place slowly. At this time, the specimens had insufficient cohesive strength and were too fragile and 'crumbly' to be tested.

After 48 hours curing, one specimen was tested to observe whether it could withstand the minimum applied force of 411N. The specimen was mounted on the apparatus and no conditioning pulses were applied. After the fourth pulse, the lateral transducers attached to the specimen were pushed out of the allowable strain for modulus calculations. The horizontal strain obtained at the smallest force applied was greater than 100με, as shown in Table 5.3. As 100με is the maximum allowable strain, the modulus value calculated was the average of four pulses. After five days curing, only one specimen was tested because five conditioning pulses resulted in excessive horizontal strains. However, an average modulus of 241MPa was calculated for these pulses. At the end of 13 days curing, only one specimen could be tested for modulus because of limited access to test equipment at this time. After 28 days, five specimens were successfully tested, producing acceptable values of strain and, therefore, modulus. Six specimens were tested after 57 and 117 days. The six specimens tested were the five tested after 28 days and the specimen tested after 13 days.

From the results in Table 5.3 it can be observed that the specimen mass decreases to reach a constant value. As the moisture evaporates, the rejuvenator reacts with the RAP recreating the bonding action of the bitumen on the particles. The specimens then become stronger and suffer less deformation. The following figures show the increase of modulus and decrease of mass with time of specimens cured at 25°C (room temperature).

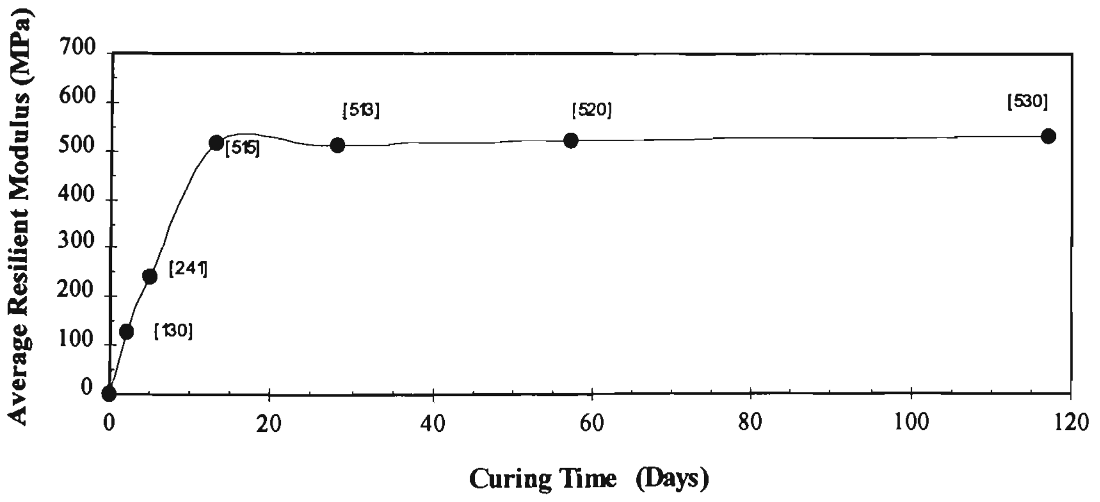

Figure 5.5 **Average resilient modulus versus curing time for specimens cured at room temperature (Group 1).**

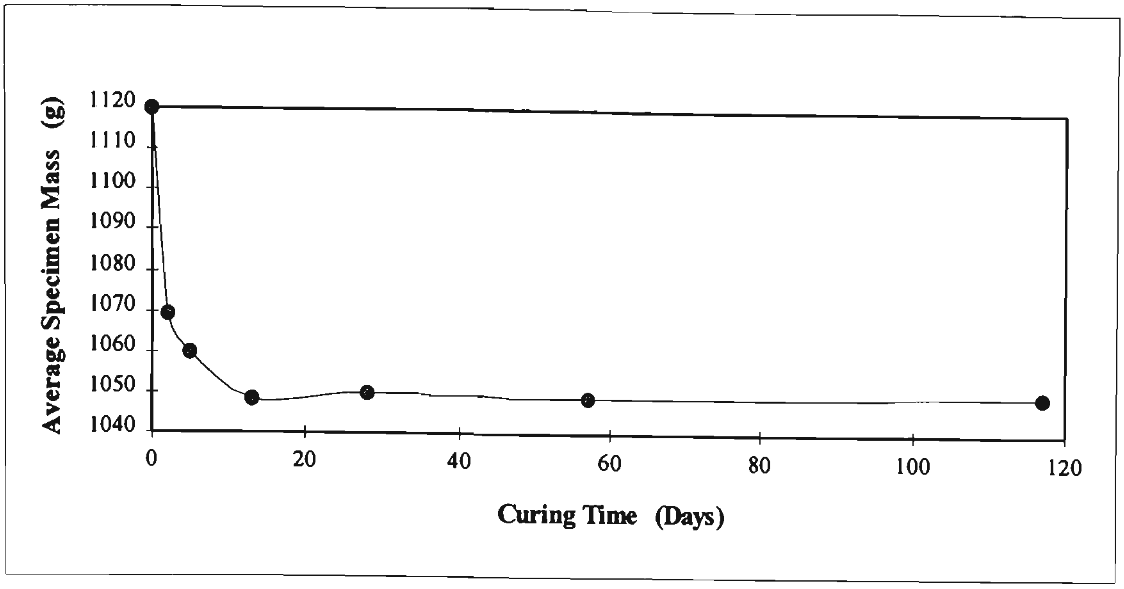

Figure 5.6 Average specimen mass versus curing time for specimens cured at room temperature (Group 1).

5.2.1.2 Group 2

Group 2 consisted of curing specimens at 60°C for 24 hours before being tested for modulus. Specimens were subsequently kept at the curing temperature and tested at increasing intervals of time. The results obtained on RAP specimens in this group are shown in Table 5.4. The individual results obtained for each specimen are presented in Appendix H2.

TIME ELAPSED	AVERAGE SPECIMEN MASS (g)	AVERAGE APPLIED FORCE (N)	AVERAGE HORIZONTAL STRAIN (με)	AVERAGE RESILIENT MODULUS (MPa)	AVERAGE BULK DENSITY (kg/m^3)	No. OF SPECIMENS TESTED
0	1120.0	-	-	-	2141.4	5
1	1058.0	403	82.6	495	2022.6	5
4	1049.0	396	45.8	876	2005.5	3
8	1049.1	406	42.5	975	2005.7	5
15	1049.1	400	41.9	965	2004.3	5
30	1049.4	409	40.4	1029	2006.1	5
57	1048.0	403	36.0	1129	2003.5	5
113	1048.1	401	31.6	1289	2003.8	5

Table 5.4 Average test results obtained for specimens cured at 60°C (Procedure One, Group 2).

All specimens in this group were strong enough to be tested after 24 hours curing at 60°C. After this period of time, most of the moisture had evaporated and some strength had been achieved.

After 4 days curing, three specimens only were tested in an attempt to keep the testing apparatus usage to a minimum. However, on reflection, it was thought better to test all five specimens at each test time. Figures 5.7 and 5.8 show the changes of modulus and specimen mass of the compacted RAP specimens.

From Figure 5.7 the rapid increase in modulus during the first 8 days of curing, can be observed after which a small but continuous increase in modulus occurred. Just before the tests at 15 days, the curing oven stopped working for 4 days and the curing temperature reduced to about 25°C for that time. This seems to be a reasonable explanation for the slight drop in average modulus for the specimens tested at that time.

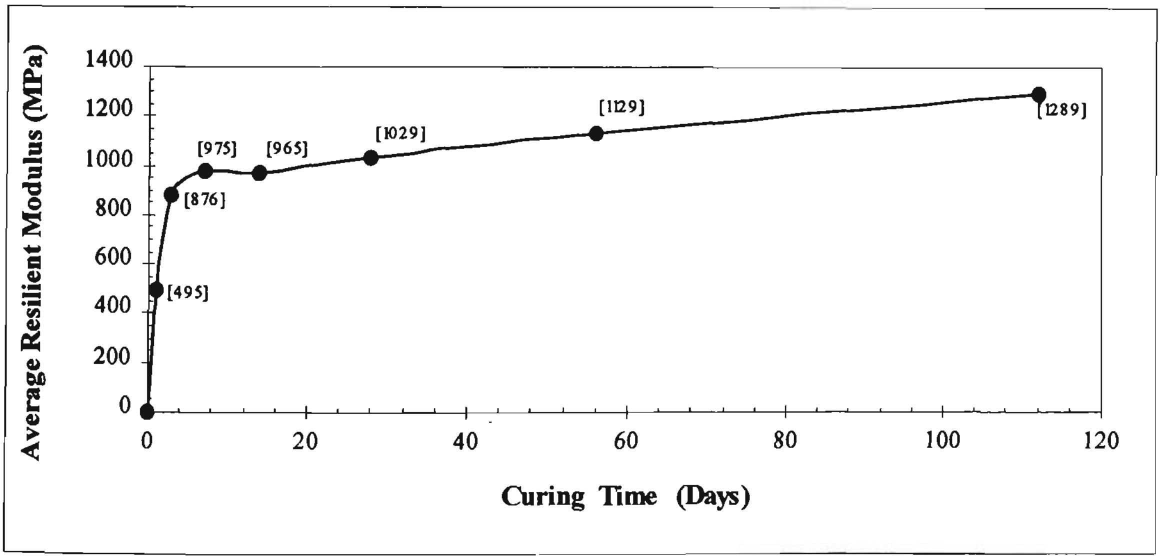

Figure 5.7 Average resilient modulus versus curing time for specimens cured at 60°C (Group 2).

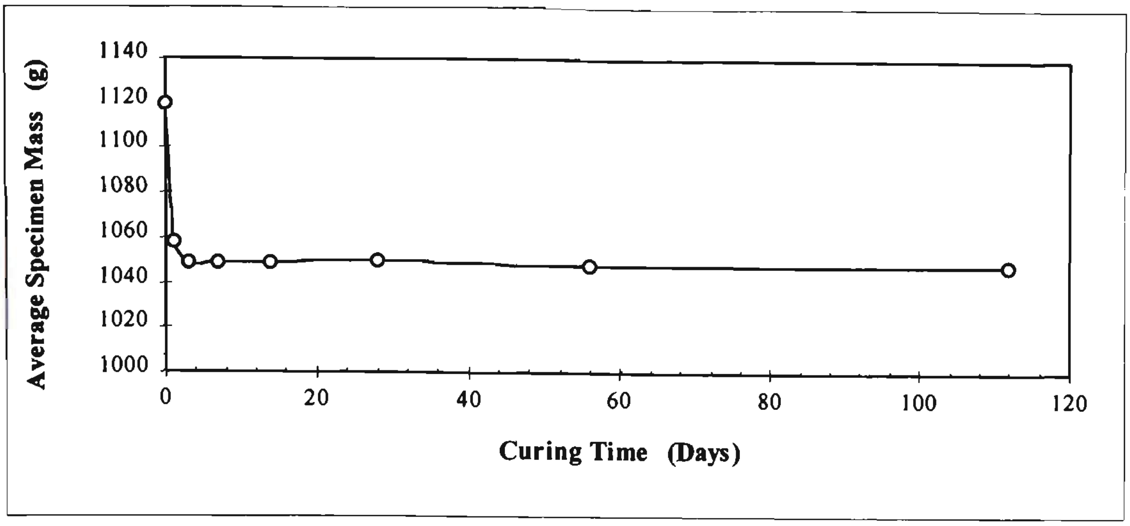

Figure 5.8 Average specimen mass versus curing time for specimens cured at 60°C (Group 2).

5.2.1.3 Group 3

Specimens from this group were cured at 90°C for 24 hours before being tested for modulus. They were continuously cured and tested at increasing intervals of time. The results obtained on RAP specimens in this group are shown in Table 5.5. Results for each specimen are presented in Appendix H3.

TIME ELAPSED (Days)	AVERAGE SPECIMEN MASS (g)	AVERAGE APPLIED FORCE (N)	AVERAGE HORIZONTAL STRAIN (με)	AVERAGE RESILIENT MODULUS (MPa)	AVERAGE BULK DENSITY (kg/m³)	No. OF SPECIMENS TESTED
0	1120.0	-	-	-		5
1	1050.8	401	51.6	787	2010.1	5
3	1048.5	403	42.4	959	2006.5	3
7	1045.8	405	41.7	987	1999.3	3
14	1046.7	405	32.1	1276	2002.3	5
28	1045.9	1170	55.1	2164	2001.0	4
57	1045.8	1191	37.2	3252	2000.9	4
118	1046.6	1195	26.7	4534	2002.3	4

Table 5.5 Average test results obtained for specimens cured at 90°C (Procedure One, Group 3).

All specimens in this group were strong enough to be tested after 24 hours curing at 90°C. After this period of time, almost all the moisture had evaporated and therefore stronger specimens were obtained.

After 3 and 7 days curing, three specimens were tested in an attempt to keep the testing apparatus usage to a minimum. However, as in Group 2, it was later thought better to keep testing all five specimens at each test time. After an initial rapid increase in modulus during the first week, corresponding to the rate of moisture loss, the specimens show a steady and quite large increase in modulus with further curing at 90°C. Figures 5.9 and 5.10 show the changes of modulus and specimen mass of the compacted RAP specimens cured at 90°C.

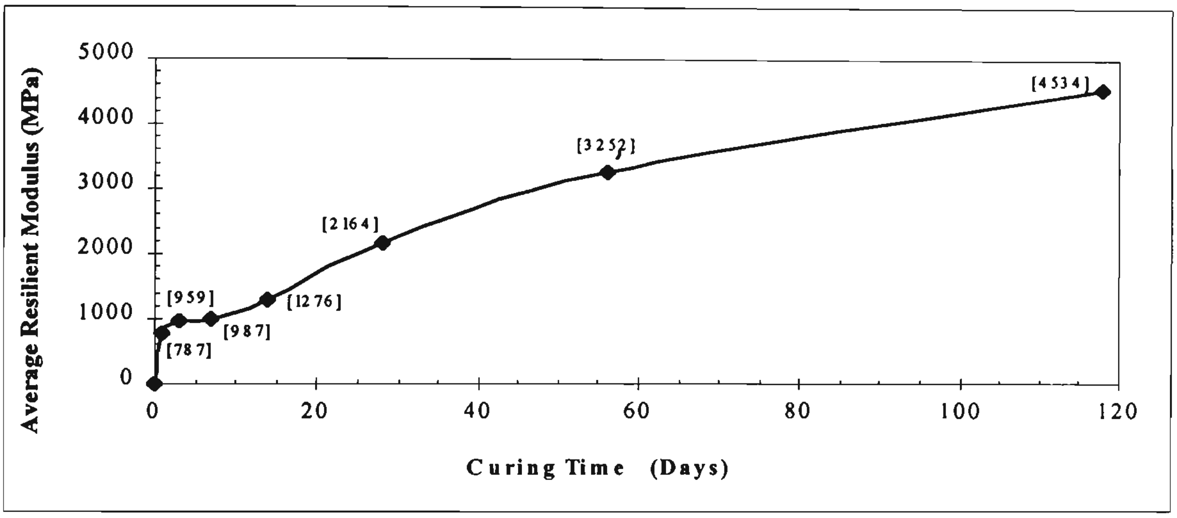

Figure 5.9 Average resilient modulus versus curing time for specimens cured at 90°C (Group 3).

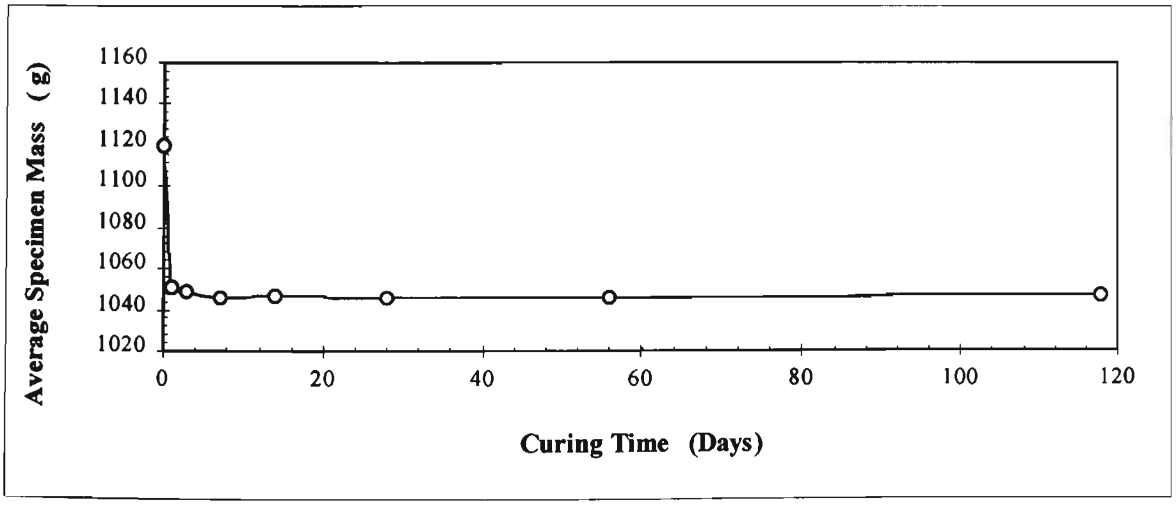

Figure 5.10 Average specimen mass versus curing time for specimens cured at 90°C (Group 3).

5.2.2 Selection Of Curing Temperature

As stated in Chapter 4, the curing temperature to be used in Procedures Two and Three was selected from Groups 1 to 3 in Procedure One. The temperature selected was that which gave the maximum resilient modulus after specimens had been cured for 24 hours.

As the temperature giving maximum modulus after 24 hours was 90°C, it was chosen. The modulus was 37% higher than that obtained at 60°C. The specimens cured at room temperature were found to be too weak to test after 24 hours.

It was noted that, for specimens cured at both 60°C and 90°C, after 24 hours most of the moisture had evaporated and therefore the rejuvenating action had taken place. Therefore, there was no difference between the curing temperatures in this regard.

5.2.3 Procedure Two

Specimens for this procedure were stored loose at room temperature for 6 hours in open trays. Some moisture loss occurred during this period and it was replaced before compaction to facilitate the workability of the mix in the gyratory compactor. After the addition of moisture, the material was mixed thoroughly. Specimens were then compacted following the procedure outlined in Appendix C. It was recognised that covering the trays to help minimise moisture loss would have been a good idea. The water added to the specimens, did not seem to have had any affect on their density.

After 24 hours curing at 90°C, specimens were tested for resilient modulus. The averaged result of five specimens was 1085MPa. Compared with the value of 789MPa for the Procedure Two, Group 3 specimens, this increase in modulus indicates that the 6 hours of loose storage had caused faster rejuvenating action of the emulsion.

When all the specimens were tested for modulus the question was raised of whether specimens should continue being cured at 90°C, or if testing should finish at this point. The decision on continuing the curing process was made in order to observe whether the selected curing temperature would cause an unacceptable amount of oxidation of the rejuvenator with time, as measured by change in viscosity.

Table 5.6 shows the average results obtained from this procedure. Specimens were not tested after 2 and 4 days because the testing apparatus was unavailable at those times. The numerical results obtained for each specimen are presented in Appendix H4.

TIME ELAPSED (Days)	AVERAGE SPECIMEN MASS (g)	AVERAGE APPLIED FORCE (N)	AVERAGE HORIZONTAL STRAIN (με)	AVERAGE RESILIENT MODULUS (MPa)	AVERAGE BULK DENSITY (kg/m^3)	No. OF SPECIMENS TESTED
0	1120.0	-	-	-	2138.6	5
1	1067.9	407	38.2	1085	2041.0	5
8	1065.6	1167	74.3	1598	2036.6	5
22	1066.1	1171	61.5	1919	2036.9	5
50	1065.3	1188	41.7	2877	2036.0	5
98	1066.0	1191	31.7	3796	2037.3	5
106	1065.2	1208	29.1	4180	2035.9	5

Table 5.6 Average test results obtained for specimens stored loose at room temperature for 6 hours and cured at 90°C (Procedure Two).

From Table 5.6 it is observed that resilient modulus continues to increase with time. In the test done after 8 days curing using an applied force of 411N, the horizontal strains were less than the required minimum to calculate the modulus, and the applied compressive force had to be increased to 1200N. This force was used for all remaining tests. Figure 5.11 depicts the increase in modulus with time. Figure 5.10 depicts the decrease in specimen mass with time.

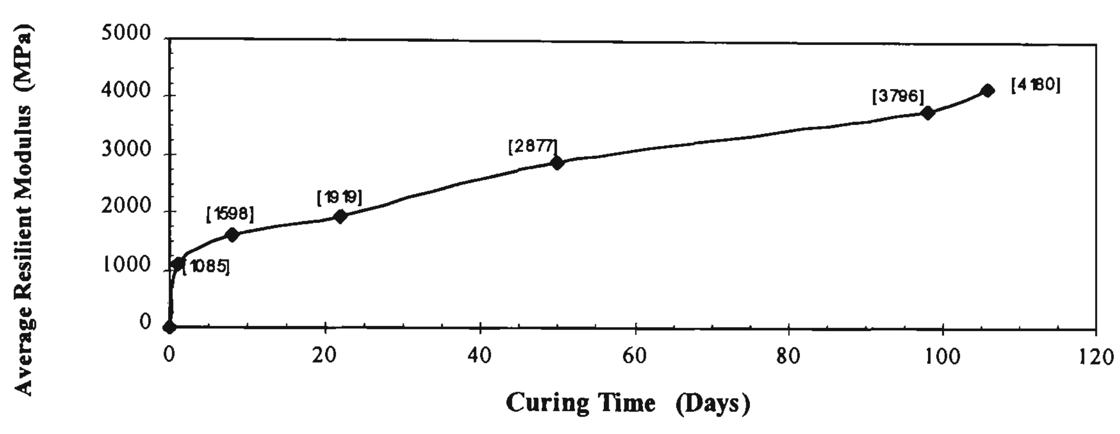

Figure 5.11 **Average resilient modulus versus curing time for specimens stored loose at room temperature and cured at 90°C (Procedure Two).**

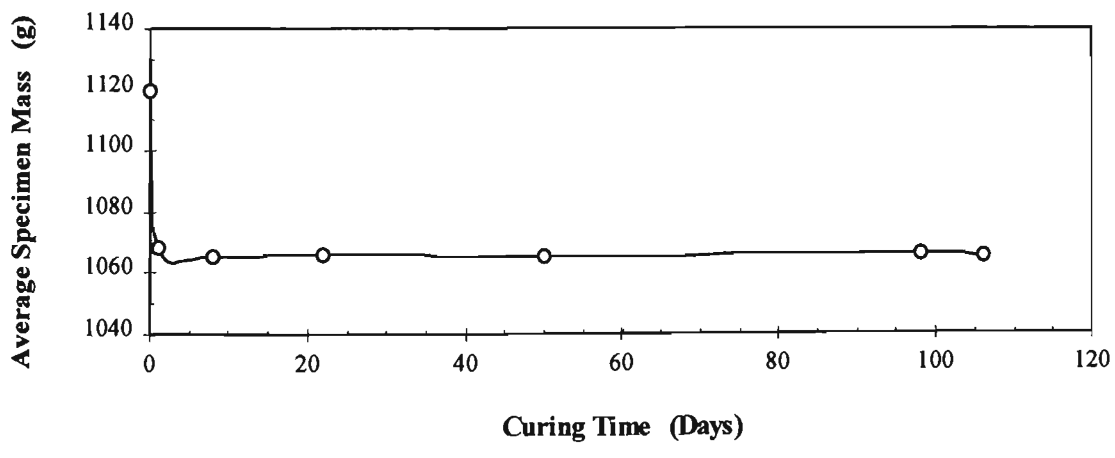

Figure 5.12 **Average specimen mass versus curing time for specimens stored loose at room temperature and cured at 90°C (Procedure Two).**

5.2.4 Procedure Three

Specimens were stored loose at 60°C for 6 hours before being compacted. As in Procedure Two, specimens were stored loose in open trays where moisture evaporation took place. The lost moisture was then replaced by adding water at 60°C, since specimens were stored at this temperature. This addition of water to the specimens did seem to produce a slight change in density of the compacted specimens.

Five specimens were tested after 24 hours curing at 90°C and the average resilient modulus obtained was 858MPa. A large increase in modulus followed as the curing time increased. The results obtained are shown in Table 5.7. The numerical results obtained for each specimen at each testing period are presented in Appendix H5.

TIME ELAPSED (Days)	AVERAGE SPECIMEN MASS (g)	AVERAGE APPLIED FORCE (N)	AVERAGE HORIZONTAL STRAIN ($\mu\varepsilon$)	AVERAGE RESILIENT MODULUS (MPa)	AVERAGE BULK DENSITY (kg/m^3)	No. OF SPECIMENS TESTED
0	1120.0	-	-	-	2157.4	5
1	1055.4	412	50.3	858	2028.0	5
7	1049.4	1169	94.2	1288	2016.5	5
22	1049.0	1181	67.0	1827	2014.7	5
50	1048.5	1183	43.2	2830	2014.8	5
84	1048.9	1182	32.4	3854	2015.7	5
106	1047.9	1161	25.3	4848	2013.7	5

Table 5.7 Average test results obtained for specimens stored loose at 60°C for 6 hours and cured at 90°C (Procedure Three).

Figures 5.13 and Figure 5.14 depict the increase of modulus with time after specimens were stored loose at 60°C and cured at 90°C.

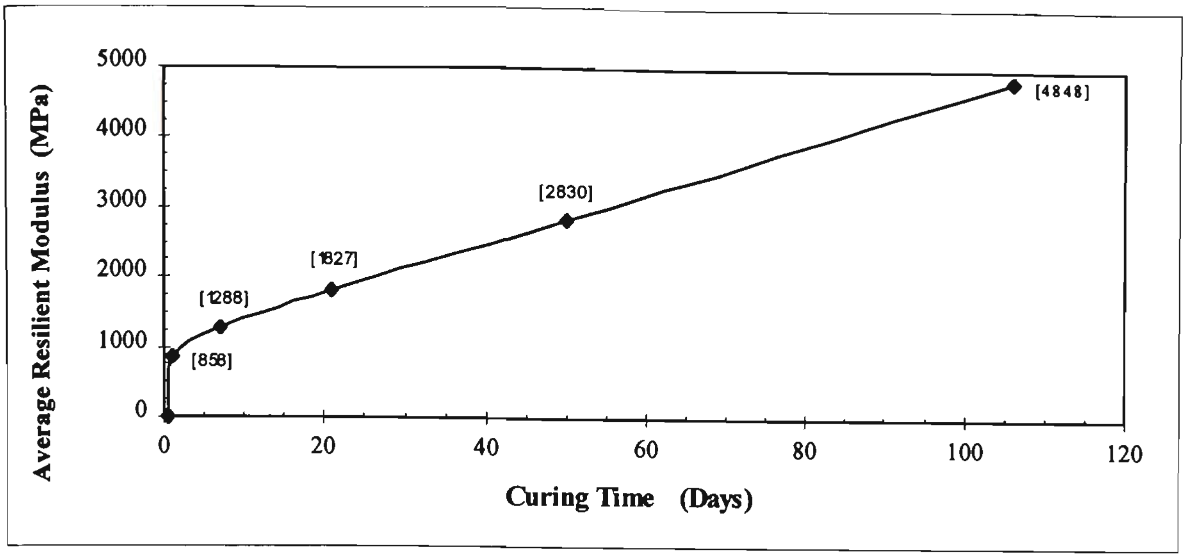

Figure 5.13 Average resilient modulus versus curing time for specimens stored loose at 60°C and cured at 90°C (Procedure Three).

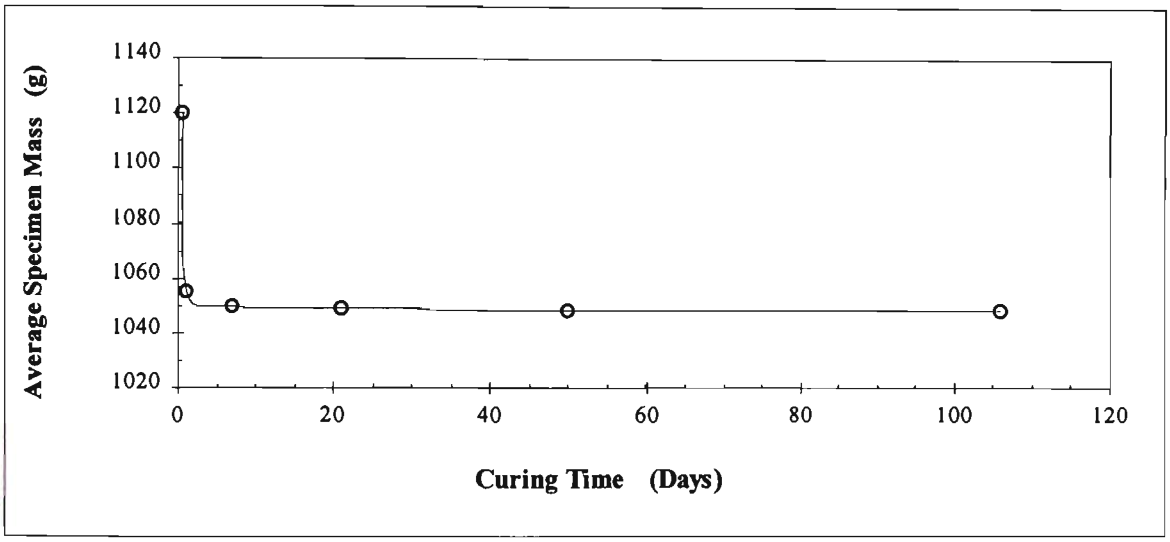

Figure 5.14 Average specimen mass versus curing time for specimens stored loose at 60°C and cured at 90°C (Procedure Three).

5.3 VISCOSITY TEST

The viscosity tests were done after all modulus testing was completed. Because of limited availability of testing facilities (and the long duration and high cost involved in the viscosity testing) only ten tests were done. It was proposed to perform only one test on untreated RAP, but two were actually required. Specimens were selected on the following basis:

1. RAP. As a reference value, and to see what a typical value is for RAP.
2. Specimens from Procedure One, after curing at 25°C and 60°C. For the 25°C curing, because this is the likely average curing temperature of material in road pavements. For 60°C curing, because it was felt that this was likely to be the best curing temperature for the proposed laboratory preparation procedure.
3. Specimens from Procedure Two. Because these gave the greatest modulus in the shortest period of time - a value higher than that of untreated RAP - and it was desired to determine whether this was due to greater effectiveness of the binder, or due to oxidation.

The first specimen of untreated RAP material was tested at 25°C. It was thought that the rejuvenated bitumen would be soft and, in order to compare results, it was required that all tests were done at the same temperature. However, the test became too slow due to the high viscosity of the material and, to obtain results in reasonable time, short cuts had to be made on the number of loads applied per plate, which gave inaccurate results. The results obtained from this test were disregarded and the testing temperature changed to 45°C. The second specimen was then successfully tested at 45°C. This was then chosen as the testing temperature, not only to facilitate the testing of the untreated material and of specimens that had been cured at elevated temperatures for longer periods of time resulting in a stiffer binder, but also to reduce the usage time of the apparatus. Viscosity results for each specimen tested are presented in Appendix I.

5.3.1 Viscosity of Bitumen in RAP

The viscosity of RAP was measured to determine how oxidised the material was prior the addition of the rejuvenator. The results obtained from this test were to be used to compare with the viscosity resulting from the other procedures in order to determine how the rejuvenator reacts with the oxidised RAP. From this test, it was found that the average viscosity of the RAP at 45°C was 178kPa.s (169 - 185kPa.s) at a shear rate of $5ms^{-1}$.

5.3.2 Viscosity of Specimens Cured at Room Temperature (Procedure One, Group 1)

Specimens cured at room temperature (25°C) were tested for viscosity to observe how the rejuvenator works at this temperature. This would help in understanding what actually occurs to the material when it is used in pavement construction. As stated earlier, three specimens were tested for viscosity at three different stages of the curing process.

The first specimen was tested at the time at which a modulus result was first obtainable, in this case 48 hours. The second specimen was tested for viscosity after 8 days in order to compare the result with the other specimens tested at the same time. This will allow the observation of the change in viscosity with time. However, it would have been ideal to test it at the time at which the rapid increase in modulus was observed (13 days). The last specimen used was randomly selected at the end of the modulus testing after 117 days. The first two specimens were mixed, compacted and cured at room temperature for the required period of time, following the same procedure used to create the specimens earlier tested for modulus. The viscosity test results are summarised in Table 5.8.

CURING TIME (Days)	AVERAGE Log VISCOSITY	AVERAGE VISCOSITY (kPa.s)	AVERAGE RESILIENT MODULUS (MPa)
2	3.88	8	130
8	3.93	8	366
117	4.24	18	533

Table 5.8 Results obtained from viscosity tests at 45°C and the respective resilient modulus (Procedure One, Group 1).

Figure 5.15 shows the increase in viscosity with curing time, for specimens cured at room temperature (25°C).

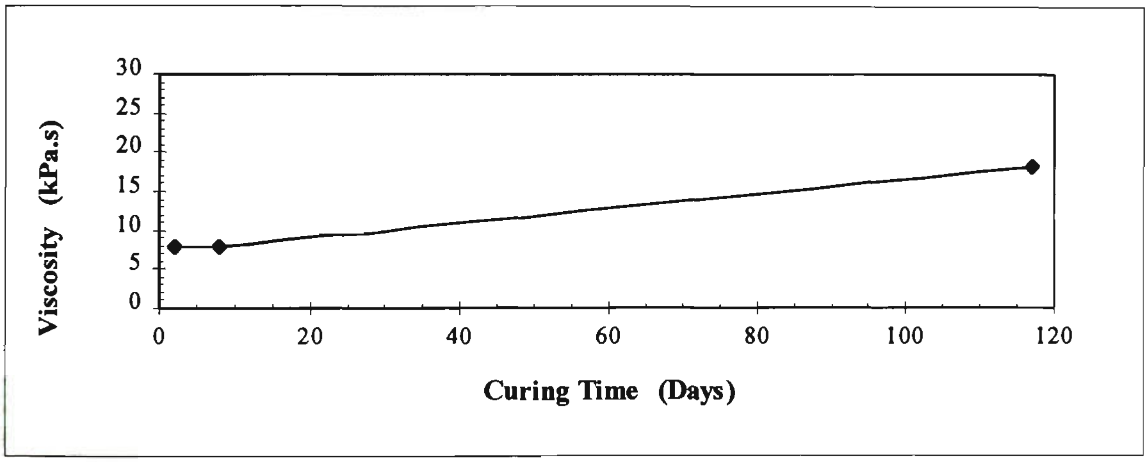

Figure 5.15 Viscosity versus curing time for specimens cured at room temperature (Procedure One, Group 1).

5.3.3 Viscosity of Specimens Cured at 60°C (Procedure One, Group 2)

Viscosity was determined on three specimens, and because the test was performed at the end of the modulus testing, the first two specimens had to be prepared to simulate the specimens originally tested for modulus. The prepared specimens were mixed, compacted and cured for the purpose of the viscosity test, following the same manner as the specimens used for modulus testing. One specimen was tested for viscosity after 24 hours curing, at which time a modulus was obtainable. The second specimen was tested after 8 days curing, at which time maximum modulus was attained.

The third specimen was selected at random from the specimens tested for modulus, after 113 days curing. All specimens were wrapped up in plastic and kept in a dark place until being tested for viscosity. This was done to stop the interaction of air and light with the specimen (Hunter, 1994). These two factors are known to be responsible for the oxidation of bituminous binders, so by wrapping and placing the specimens away from light the oxidation process is minimised and perhaps stopped.

The results obtained are summarised in Table 5.9. It can be observed that at 60°C an increase in viscosity occurs and, therefore, this results in an increase in modulus. The increase in viscosity is depicted in Figure 5.16.

CURING TIME (Days)	AVERAGE Log VISCOSITY	AVERAGE VISCOSITY (kPa.s)	AVERAGE RESILIENT MODULUS (MPa)
1	4.01	10	495
8	4.19	16	975
113	4.48	30	1289

Table 5.9 Results obtained from the viscosity tests at 45°C and the respective resilient modulus (Procedure One, Group 2).

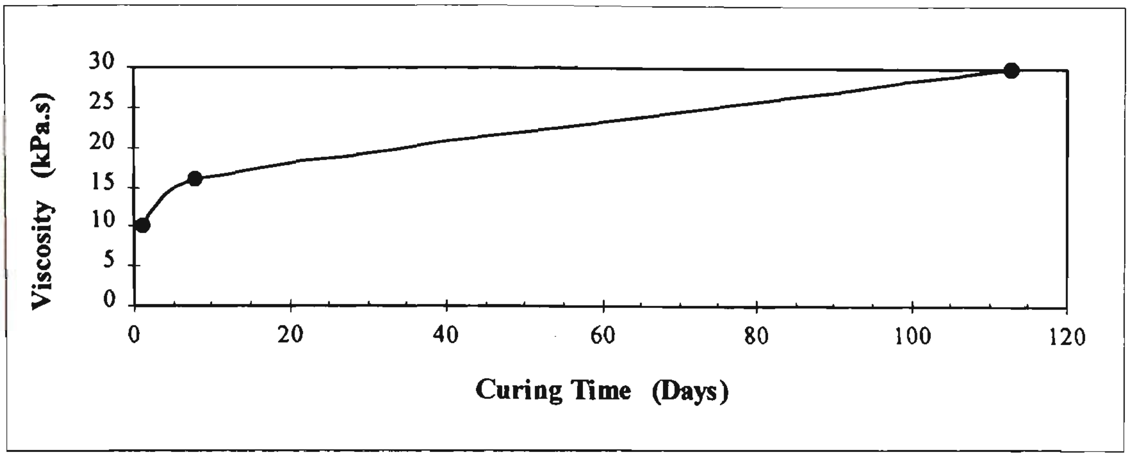

Figure 5.16 **Viscosity versus curing time for specimens cured at 60°C (Procedure One, Group 2).**

5.3.4 Viscosity of Specimens Stored Loose at 60°C and Cured at 90°C (Procedure Three)

For this Procedure, only two specimens were tested for viscosity. This was due to the necessity of testing the second untreated RAP sample at 25°C, reducing the number of remaining test specimens from nine to eight.

One specimen was tested after 24 hours curing, which was the time at which the first modulus result was obtained. The specimen was mixed, stored loose at 60°C for 6 hours, compacted and cured at 90°C for the purpose of the viscosity test to simulate the specimens previously tested for modulus. The second specimen tested had been cured for 106 days.

The viscosity test results are summarised in Table 5.10. The results obtained show an extremely high value of viscosity after 106 days which is not surprising, given the high modulus value. This was also evident during the working of the viscosity plates where an extremely high hand pressure had to be applied in order to obtain the required film thickness. The plates had to be heated up under a tungsten lamp for very short periods of time and worked immediately to stop the film from cooling and therefore becoming too hard to work.

CURING TIME (Days)	AVERAGE Log VISCOSITY	AVERAGE VISCOSITY (kPa.s)	AVERAGE RESILIENT MODULUS (MPa)
1	4.00	10	858
106	7.17	15000	4848

Table 5.10 Results obtained from the viscosity tests at 45°C and the respective resilient modulus (Procedure Three).

Figure 5.17 shows the increase in viscosity with time for specimens stored loose at 60°C for 6 hours and cured at 90°C. Figure 5.18 shows the increase in viscosity with time for all specimens tested.

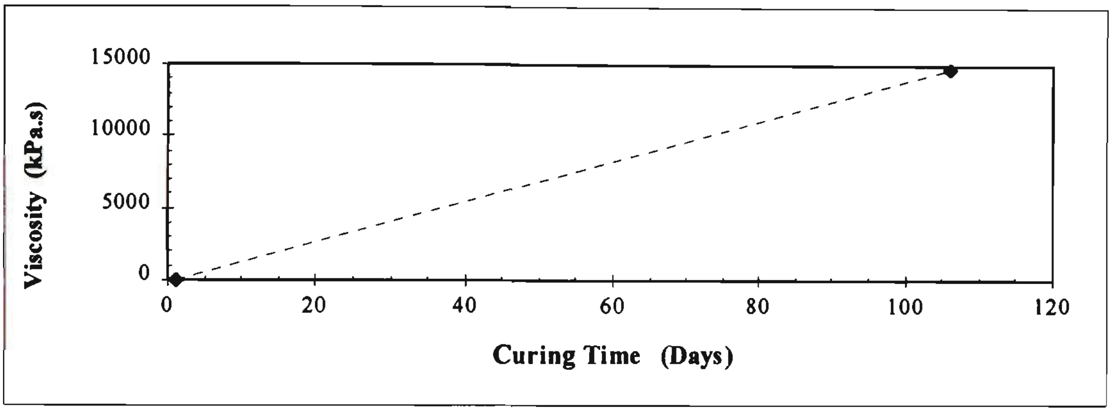

Figure 5.17 Viscosity versus curing time for specimens stored loose at 60°C and cured at 90°C (Procedure Three).

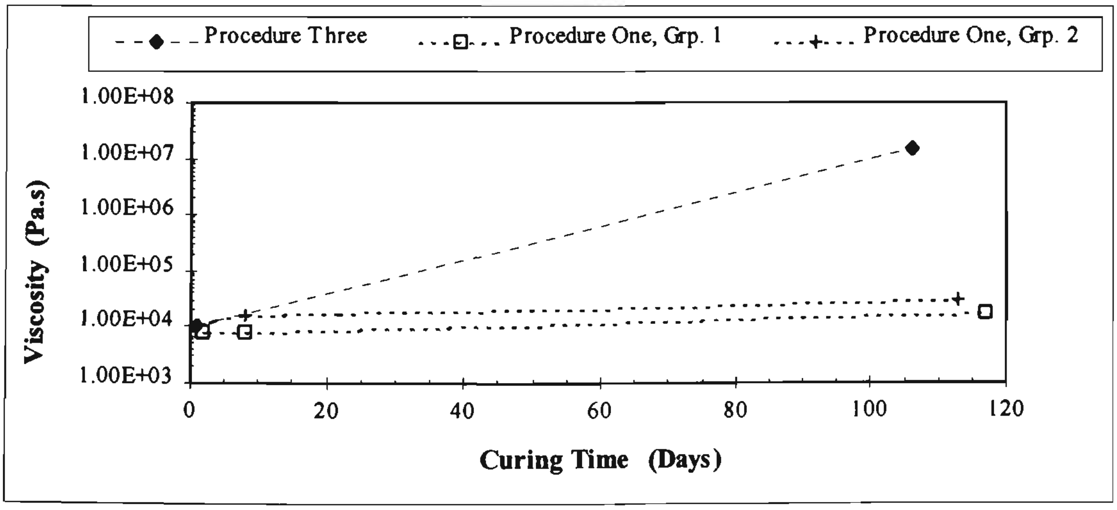

Figure 5.18 Viscosity versus curing time for specimens all specimens tested.

CHAPTER 6 *INTERPRETATION OF RESULTS*

6.1 GRADING

The results from the gradings of RAP and the clean aggregate are presented in Appendix A. Table 6.1 shows the average percentage passing for RAP and clean aggregate together with the Vic Roads Standard Specification for Road Works Section 407Q Mix Design Requirements for Hot Asphalt Mixes for a 20mm mix. From this it can be observed that:

i) The RAP grading is coarser than that of the clean aggregate throughout.

ii) The clean aggregate grading is finer than the Vic Roads minimum, except at the 0.150mm size.

SIEVE SIZE mm	CUMULATIVE PERCENTAGE PASSING			
	RAP	CLEAN AGGREGATE	VIC ROADS MINIMUM	VIC ROADS MAXIMUM
26.5	100	100	100	100
19.0	99.5	99.7	95	100
13.2	89.5	94.1	77	90
9.5	77.6	87.1	63	80
6.70	63.1	77.8	52	65
4.75	50.0	67.4	45	55
2.36	31.5	52.3	30	43
1.18	18.9	40.9	20	35
0.600	10.3	32.2	14	27
0.300	4.34	22.8	9	21
0.150	1.34	13.2	7	15
0.075	0.38	8.92	3	6

Table 6.1 Cumulative percentage passing for RAP, clean aggregate and Vic Roads requirement limits for asphalt.

The grading of the RAP is coarser because the bitumen binds some of the particles together. Also the increase of fines in comparison to the Vic Roads specifications may be due to the crushing process, which can break the aggregate into smaller pieces. The aggregate originally used may have been outside the Vic Roads limits but, as the stockpile material came from a number of road pavements which would have to comply with Vic Roads specifications, this seems unlikely. Figure 6.1 shows the particle size distribution of RAP and clean aggregate, and the Vic Roads specification limits.

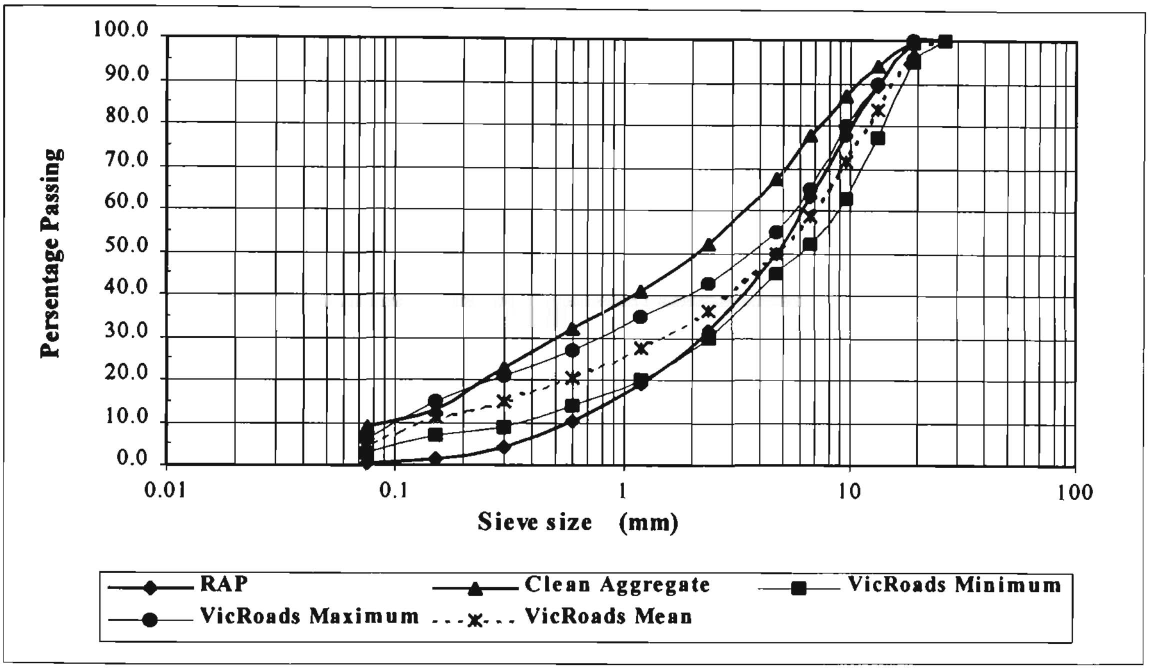

Figure 6.1 Particle size distribution for RAP, clean aggregate and Vic Roads specifications.

As already noted, the clean aggregate grading falls outside the maximum limit of Vic Roads specifications for most of its particle sizes. In other words, an improvement is needed by changing the grading. This can be done by either adding new aggregate, whether virgin crushed rock or more recycled aggregate, or by wasting and adding aggregate. In this research, no adjustments were made to the specimens used for testing. A calculation showing how adjustment in RAP grading could be done is presented in Appendix D.

6.2 RESILIENT MODULUS

6.2.1 Selection of Curing Temperature

In Procedure One, specimens were mixed and compacted at 25°C, and were tested for resilient modulus at the end of a 24 hour curing period at either 25°C, 60°C or 90°C. Following this, further modulus tests were done at increasing intervals of time. The resulting average values of resilient modulus are shown in Table 6.2.

AVERAGE RESILIENT MODULUS (MPa)					
CURING TIME days	**GROUP 1 25°C**	**CURING TIME days**	**GROUP 2 60°C**	**CURING TIME days**	**GROUP 3 90°C**
1	*	1	495	1	787
2	130	4	876	3	959
5	241	8	975	7	987
13	515	15	965	14	1276
28	513	30	1029	28	2164
57	525	57	1129	57	3252
117	533	113	1289	118	4534

* Specimen too weak to be tested

Table 6.2 Average resilient modulus increase for Groups 1, 2 and 3 in Procedure One.

After 24 hours curing the Group 3 specimens gave an average resilient modulus 59% higher than those from Group 2. Specimens from Group 1 could not be tested after this period of time because they were too weak. As the objective of the study was to produce a practical and rapid procedure for making laboratory test specimens, the curing temperature which gave the greatest modulus after 24 hours (90°C) was selected as the curing temperature for the following procedures. The specimens were not tested to destruction, but were left to cure for four months at the three temperatures, with modulus testing at intervals.

The values from Table 6.2 are plotted in Figure 6.2. It is observed that the specimens cured at 25°C and 60°C showed no significant further increase in modulus after 10 to 15 days. The specimens cured at 90°C showed a similar increase during the first week to that of the specimens cured at 60°C. Thereafter, the modulus increased significantly with time, at a slowly reducing rate. The rapid initial increases in resilient modulus during the curing process shows that curing specimens at elevated temperatures accelerates the rejuvenating action, producing a stiffer material in a shorter time.

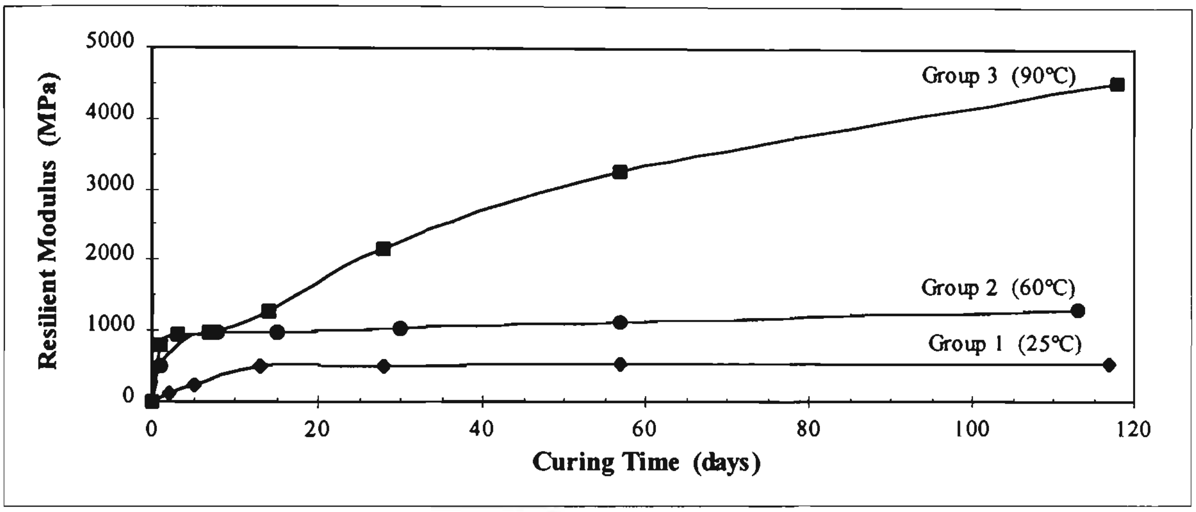

Figure 6.2 Average resilient modulus increase with time for specimens in Procedure One.

For each group of specimens tested at any one time, the mean, standard deviation and coefficient of variation were calculated. Coefficient of variation (C.V.) is defined by Best in Blake (1975) as the standard deviation expressed as a percentage of the mean, i.e.

$$\text{C.V.} = \frac{\text{Standard deviation}}{\text{Mean}} \times 100\%$$

Best states that this is a useful parameter for dealing with properties whose standard deviation rises in proportion to the mean, for instance the strengths of concrete as measured by compressive tests on cubes. It was thought that the asphalt specimens might behave similarly to concrete cubes in this respect, so it was decided to calculate C.V. for all groups. Also, C.V. is calculated and printed out in the test results obtained from the MATTA.

The C.V. values calculated for each set of modulus tests on five to six specimens varied very little with time. For Group 1 the range was 8% to 12.5%; for Group 2, 6.7% to 11.8%; and for Group 3, 7.2% to 11.3%, but with one value of 2.3% for a set of three specimens tested at 3 days. However, there was another set of three specimens in Group 3 tested at 7 days which gave a C.V. of 10.0%, which is within the range of the sets of five to six specimens. All the calculated C.V. results are presented in Appendix H.

6.2.2 Effect of Loose Storage on Resilient Modulus

Procedures Two and Three included a six hour period of loose storage of specimens at 25°C and 60°C respectively, prior to compaction, which had an effect on modulus as some of the rejuvenating action took place at this time. Modulus values during a total curing time of about three months are given in Table 6.3.

After 24 hours curing at 90°C, specimens from both procedures were tested for resilient modulus. The averaged result of five specimens from Procedure Two (1085MPa), showed an increase of 119% and 38% over that obtained in Procedure One for Groups 2 and 3 respectively, proving the effect of the loose storage in the rapid action of the rejuvenator.

AVERAGE RESILIENT MODULUS (MPa)			
PROCEDURE TWO		PROCEDURE THREE	
CURING TIME days	25°C LOOSE STORAGE 90°C CURING	CURING TIME days	60°C LOOSE STORAGE 90°C CURING
1	1085	1	858
8	1598	7	1288
22	1919	22	1827
50	2877	50	2830
98	3796	84	3854
106	4180	106	4848

Table 6.3 Average Resilient modulus increase with time for Procedures Two and Three.

The specimens from Procedure Three (loose storage at 60°C) showed an increase in modulus of 73% and 9% over that obtained in Procedure One, Groups 2 and 3 respectively, which is noticeably smaller than for Procedure Two. The reason for this is not known. It was thought that loose storage at 60°C would have a greater effect on resilient modulus than loose storage at 25°C. The only difference in treatment was that the materials were left uncovered during loose storage, and moisture had to be replaced prior to compaction. More moisture was required for the material stored at 60°C than at 25°C.

For example, for the specimens in Procedure Two (25°C loose storage and 90°C curing), the amount of water added prior to compaction was very little. This amount was sprayed onto the surface of the material, as it was observed that most water evaporated at this temperature was from the surface. On the other hand, specimens from Procedure Three lost larger amounts of moisture. An average of 66.4ml (46.8ml to 81.6ml) of water was added after loose storage at 60°C to an average mass of RAP, including rejuvenator, of 1453.1g (1407.9g to 1500.4g). This represents a 4.6% average loss in moisture, which is thought to have evaporated from the water added, together with that already in the material (IMC), rather than from the water in the rejuvenator. This is because the lost moisture could all come from the IMC plus added water, without requiring any from the rejuvenator.

The increase in modulus with time is shown in Figure 6.3. It can be observed that there is only a small difference in modulus throughout. During the first fifteen days a slightly higher modulus was achieved from Procedure Two (25°C storage), but then specimens from Procedure Three (60°C storage) gave a higher resilient modulus only after 60 days further curing.

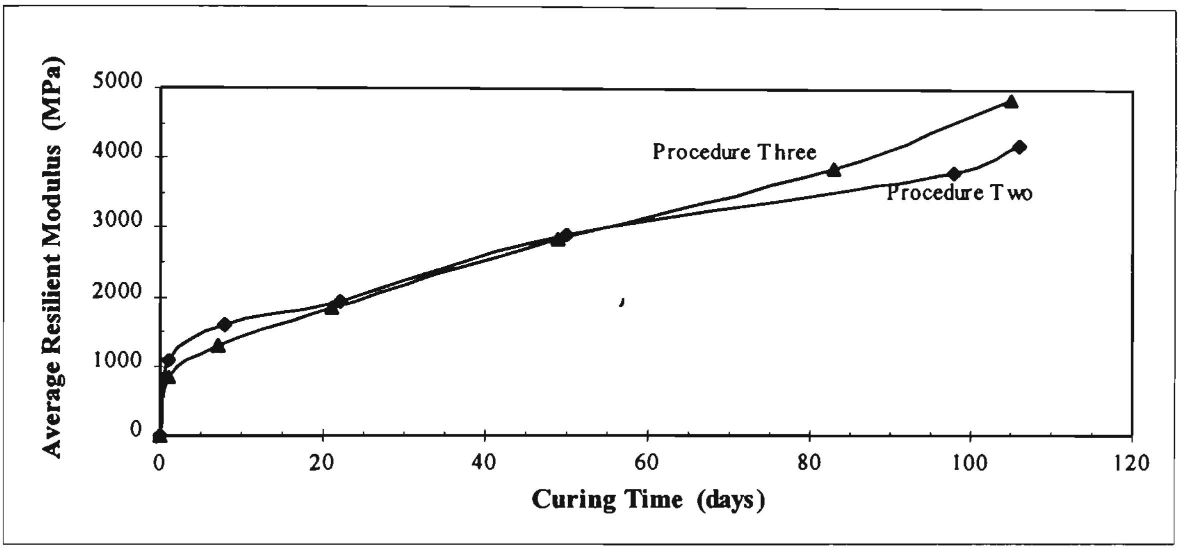

Figure 6.3 Average resilient modulus increase with time for specimens in Procedures Two (25°C loose storage) and Three (60° loose storage).

The reason for the small difference in modulus between Procedures Two and Three is not known, as it was expected that Procedure Three values would be higher in the early stages. It is thought that the amount of water added to the specimens in Procedure Three after the loose storage period may have had an influence on this behaviour. The water added possibly retarded the rejuvenating action, requiring a longer period of time for the moisture to evaporate and, therefore, for the coalescence of particles in the rejuvenator to take place.

It was not possible to do a statistical evaluation of the difference between the two procedures because there was insufficient data. Otherwise an analysis would have been done to determine whether the difference between the procedures was significant. C.V. for all sets of specimens (five in each) in Procedure Two was 10.3% at 24 hours and generally reduced with time to 4.5% at 106 days, indicating an increase in uniformity with time. Also, the values are a little less than those obtained in Procedure One.

For all sets of specimens (five in each) in Procedure Three, C.V. was noticeably greater than for Procedures One and Two, with 17.6% at 24 hours, reducing to 14.5% at 50 days, and increasing to 20.4% at 106 days. The uniformity therefore increased for the first 50 days, but then decreased during the next 50 days.

6.2.3 Effect of Curing Temperature on Moisture Loss

The loss of moisture plays an important role in the rejuvenating action of the RAP and, therefore, the gain of strength. The rate at which moisture is lost depends on the curing temperature. This can be seen in Figure 6.4 which shows the average masses over the first 20 days of curing. At elevated temperatures there is a more rapid decrease in mass.

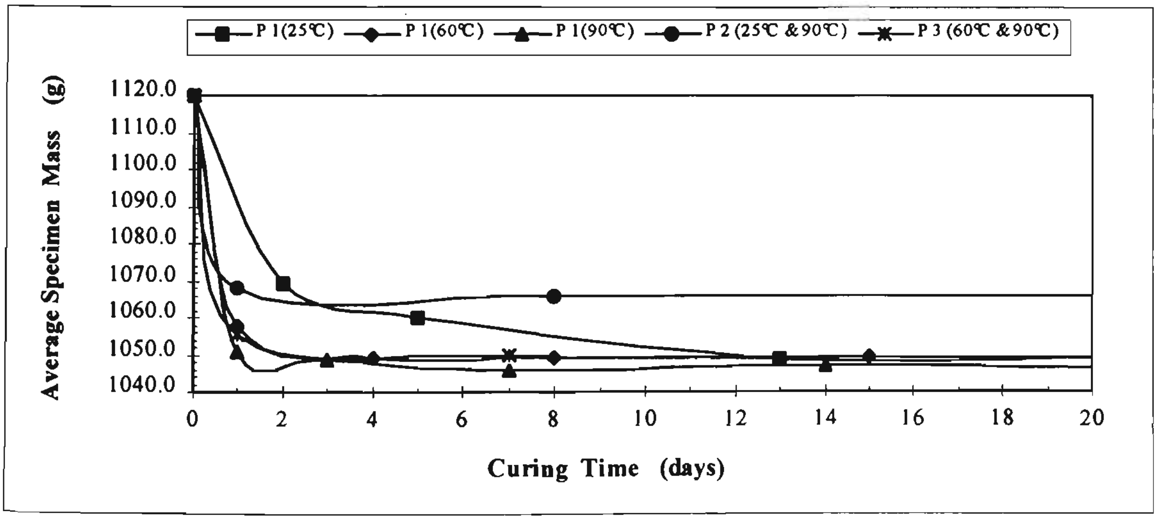

Figure 6.4 Decrease in mass of specimens in first 20 days.

Figure 6.5 shows that specimens from Procedure One, Group 3, Procedure Two and Procedure Three (which were cured at 90°C) reached more or less constant mass after 24 hours, whereas specimens from Procedure One, Groups 1 and 2 (25°C and 60°C curing, respectively) took 2 weeks to reach a constant mass. It is not known why specimens from Procedure Two had a higher mass than those from the other procedures.

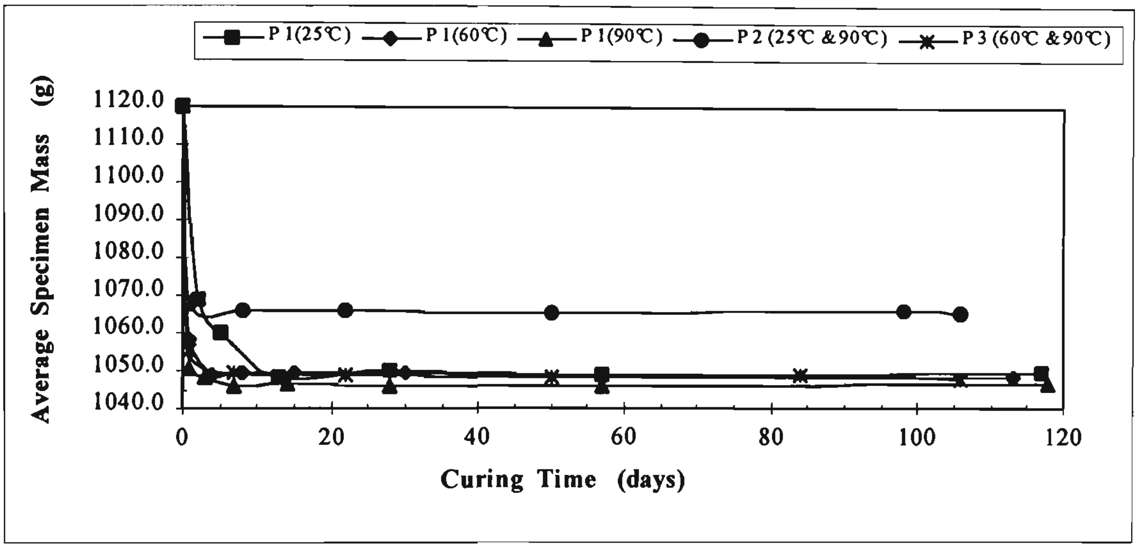

Figure 6.5 Decrease of average specimen mass with time for specimens cured at different temperatures.

6.2.4 Repeatability of Modulus Testing

AUST-001 Draft Standard for resilient modulus testing states that in any modulus test of three homogeneous specimens, the variation in modulus between each should be less than 15%, otherwise testing may be repeated or each individual specimen modulus reported. For example, for a modulus value of 1000MPa a variation of ±150MPa is allowed and at 5000MPa the acceptable variation between test specimens is 750MPa.

6.3 VISCOSITY

The aim of the program is to determine a test specimen preparation procedure which will give, in a short time, modulus values which will be similar to those achieved in pavements after the normal curing period under actual climatic conditions (say, about 2 weeks). It is assumed that the increase in modulus of a real pavement is primarily due to the increasing coalescence of the bitumen as the emulsion water evaporates, and that oxidation is minimal (Hunter, 1994). Therefore it was thought that determining viscosity with time would give a good indication of whether oxidation of bitumen in specimens cured at higher temperatures is the cause of the increase in modulus. It was expected that the specimens cured at room temperature would not show any significant increase in viscosity.

Viscosity test specimens were selected after the modulus testing was completed. Figure 6.6 shows the increase in modulus with time for all the specimens tested in this study. From this it is observed that specimens from Procedure One, Groups 1 and 2, show little or no increase in modulus with time after about 10 days, whereas specimens from Group 3 and Procedures Two and Three show a continued increase in modulus after the initial rapid increase.

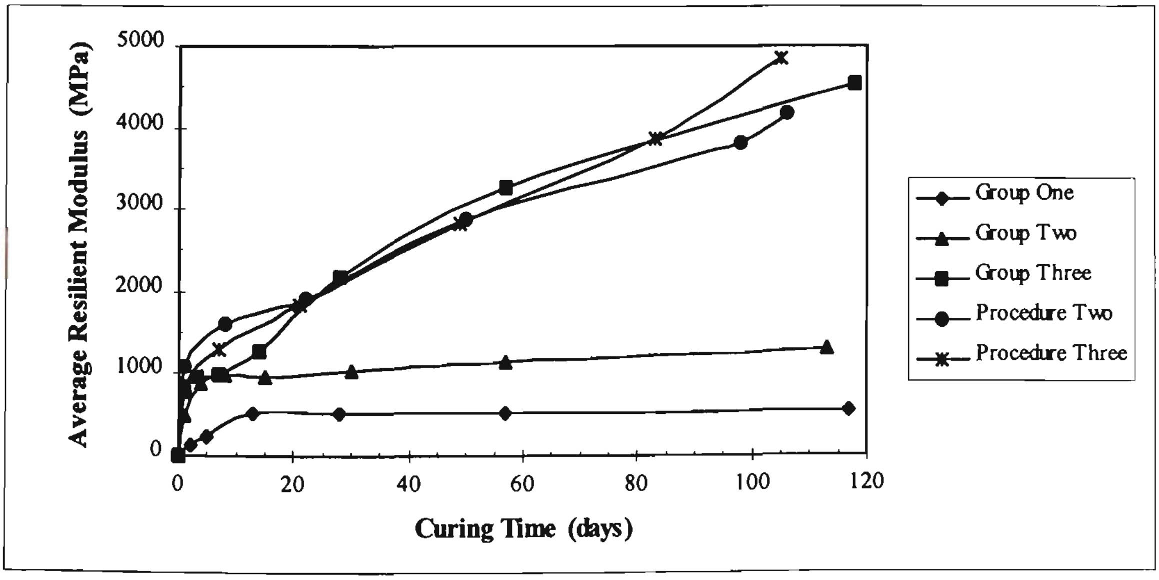

Figure 6.6 Average resilient modulus increase with curing time for each procedure.

Six specimens were selected - three each from Procedure One, Groups 1 and 2, - since these specimens produced a stable modulus result (see Figure 6.6). Specimens from Procedure Three were chosen as representing those which developed high, and increasing, modulus values (i.e. Procedure One, Group 3 and Procedure Two).

6.3.1 Viscosity of Specimens Cured at Room Temperature (Procedure One, Group 1)

The viscosity obtained from specimens cured at room temperature indicated that the rejuvenator does soften the old binder. This reaction takes place in the first few days. The viscosity at 45°C of the bitumen in the untreated RAP was found to be 178kPa.s, and after addition of rejuvenator, compaction, and curing at room temperature for 2 days the viscosity reduced to 8kPa.s. All viscosity testing was done at 45°C. Figure 6.7 shows the change of viscosity and resilient modulus with time. It is observed that viscosity remained constant at 8kPa.s after 2 days and 8 days of curing at 25°C and, at the same time, the resilient modulus is rapidly increasing.

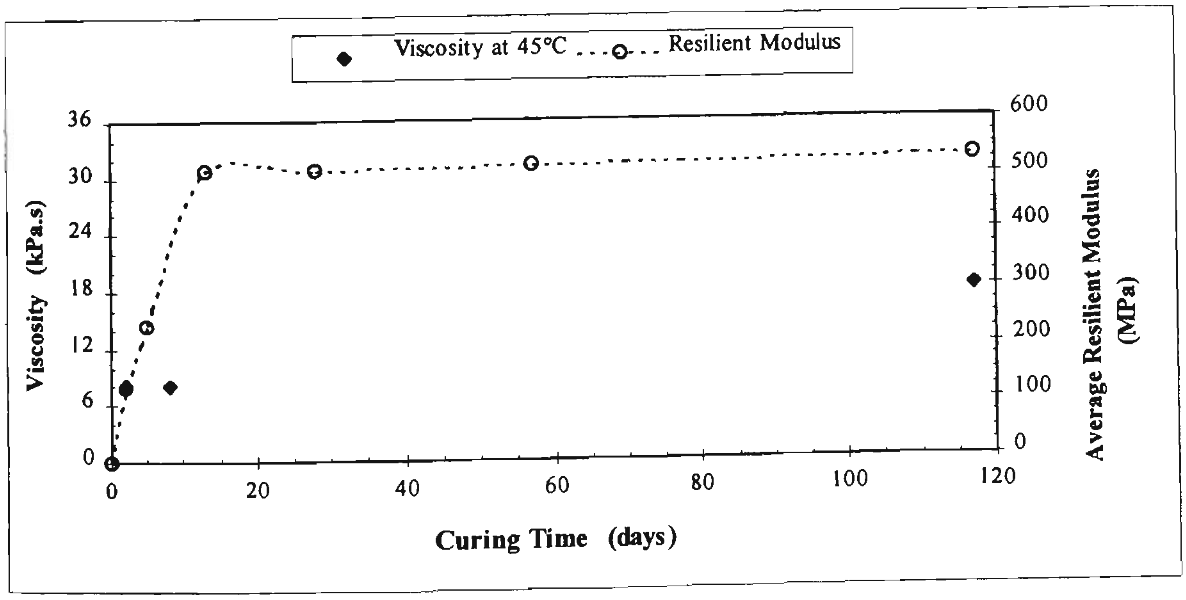

Figure 6.7 Average resilient modulus and viscosity increase versus curing time for specimens cured at room temperature (Group 1).

Only one specimen was tested at 2 and 5 days after compaction because the large horizontal strains (325με and 173με) meant that these specimens could not be re-used. Only one specimen could be tested at 13 days because of limitations on test equipment availability, although the horizontal strain of 83με was lower than the acceptable value of 100με for deformation and for the re-use of specimens.

It is thought that, during the first week or so, water is evaporating and particle coalescence is steadily increasing, causing the increase in modulus (and decrease in lateral strain). Modulus peaked at 13 days and remained essentially constant up to the last test at 117 days. At this time, bitumen viscosity had increased from 8kPa.s to 18kPa.s. This seems to indicate that this amount of viscosity increase has no effect on modulus at this temperature.

6.3.2 Viscosity of Specimens Cured at 60°C (Procedure One, Group 2)

The values of bitumen viscosity and resilient modulus with time for specimens cured at 60°C are shown in Figure 6.8.

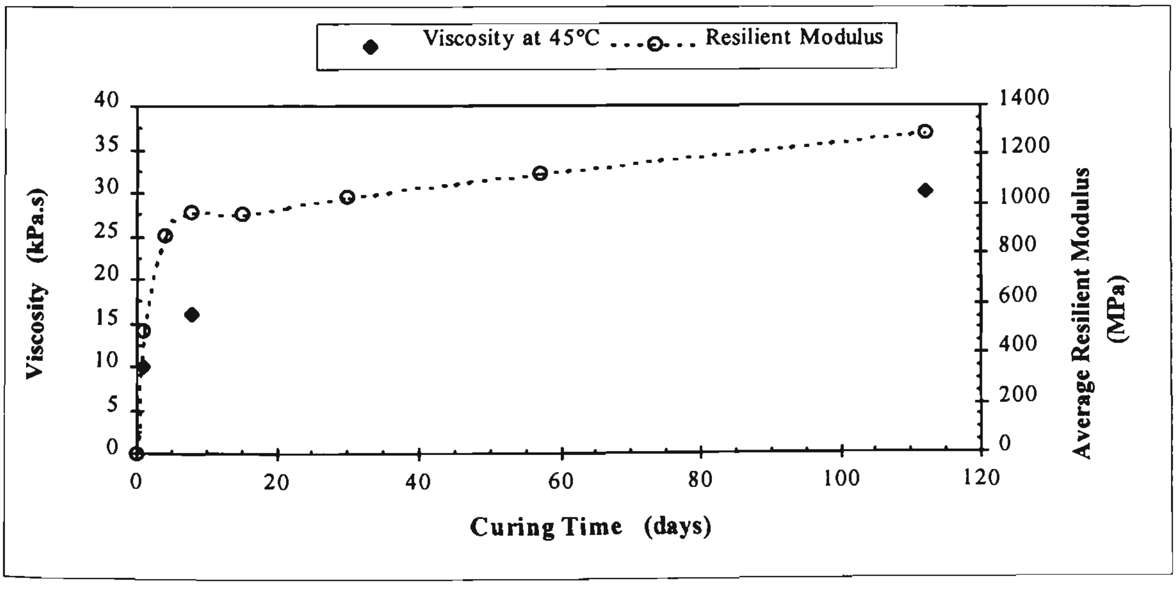

Figure 6.8 Average resilient modulus and viscosity increase versus curing time for specimens cured at 60°C (Group 2).

It is observed that there is a parallel change in viscosity and modulus. At 8 days, bitumen viscosity was 16kPa.s and modulus was 975MPa. These are approximately twice and three times, respectively, the values obtained at 8 days for the Procedure One, Group 1, specimens (8kPa.s (measured) and 350MPa (interpolated)).

After 113 days, the viscosity had increased to 30kPa.s and modulus to 1290MPa, compared with 18kPa.s and 530MPa for the room temperature cured specimens.

This seems to indicate some correlation between modulus and viscosity. The small number of viscosity determinations makes it difficult to be sure how direct the correlation is. For example, it is not known what the viscosity was when the 24 hours cured specimens reached their peak modulus value. However, it seems clear that the curing of specimens at 60°C accelerates the rejuvenating action without oxidising the bitumen, producing stiffer specimens.

6.3.3 Viscosity of Specimens Stored Loose at 60°C and Cured at 90°C (Procedure Three)

The viscosities obtained from specimens stored loose at 60°C and cured at 90°C showed interesting results. After 24 hours curing, a viscosity of 10kPa.s was measured, which is the same as that obtained from specimens cured at 60°C for 24 hours (section 6.3.2). This indicates that 24 hours curing at 90°C does not appear to damage the rejuvenator properties. However, as curing time increases, the rejuvenator is affected by the high temperature and it oxidises. This is indicated by the extremely high viscosity obtained at the end of the curing period (~15MPa.s) compared to that of the untreated RAP (178kPa.s). It is thought that this viscosity is unlikely to be reached in real cold recycled road pavements. If it did, they would be too brittle and would most likely crack. Figure 6.9 depicts the increase in viscosity and modulus for specimens cured under the same conditions.

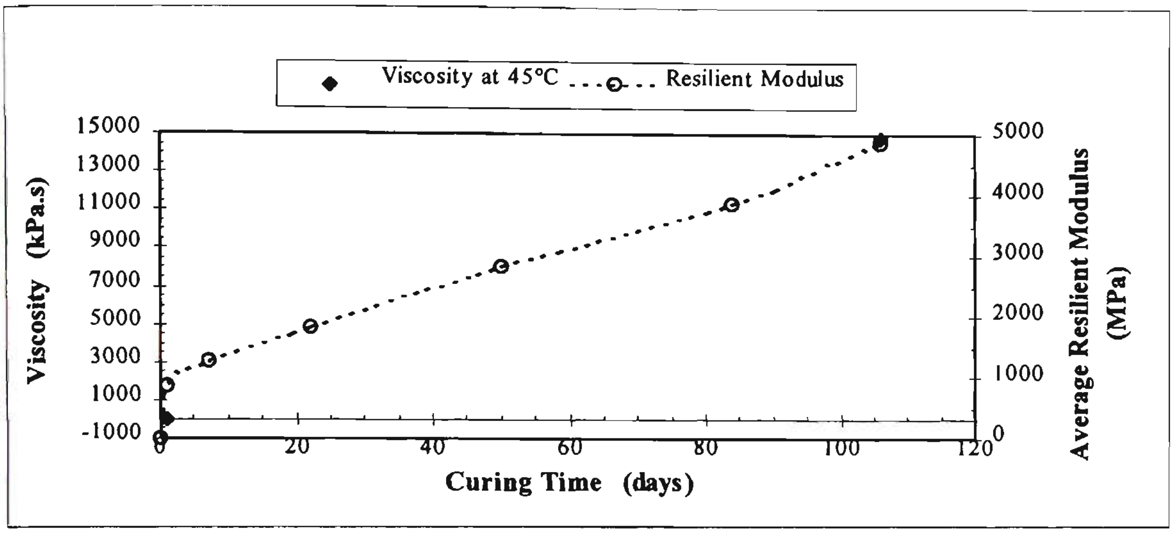

Figure 6.9 Average resilient modulus and viscosity increase versus curing time for specimens stored loose at 60°C and cured at 90°C.

It is not known at what time the material commenced to oxidise, since testing of viscosity after 8 days curing was not done because the number of tests which it was possible to do was limited by time and cost.

6.3.4 Repeatability Of Viscosity Testing

AS 2341.5 (1986) states that in any test of three specimens, if one differs by more than 0.09 logPa.s from the other two, all results should be rejected and three more plates should be prepared and tested. At the viscosities obtained in this project of about 8 to 30kPa.s, this means that the average of three results could come from values within ± 2kPa.s of the average. In other words, an average of 10kPa.s could represent a range of values between 8 and 12kPa.s.

6.3.5 Effect of Short Curing Periods at Different Temperatures

After 2 days curing at room temperature a viscosity of 8kPa.s was measured. After curing at 60°C for 24 hours, and also after 6 hours loose storage at 60°C and curing at 90°C, a viscosity of 10kPa.s was obtained in both cases. This indicates that curing at any temperature for 24 hours does not affect the viscosity of the rejuvenated bitumen, as there is no significant difference between 8 and 10kPa.s- (section 6.3.4).

6.3.6 Viscosity of Fresh Bitumen (C170)

The viscosity of fresh Class 170 bitumen was quoted by Shell (Australia) as approximately 1.5kPa.s at 45°C (Davy, 1995). It is not known what its viscosity would be after curing, but it is expected that it would rise.

CHAPTER 7 *RECOMMENDATIONS AND CONCLUSIONS*

7.1 RECOMMENDATIONS

As a result of this study, the following laboratory sample preparation procedure for the testing of cold recycled asphalt is recommended. The procedure is depicted in Figure 7.1.

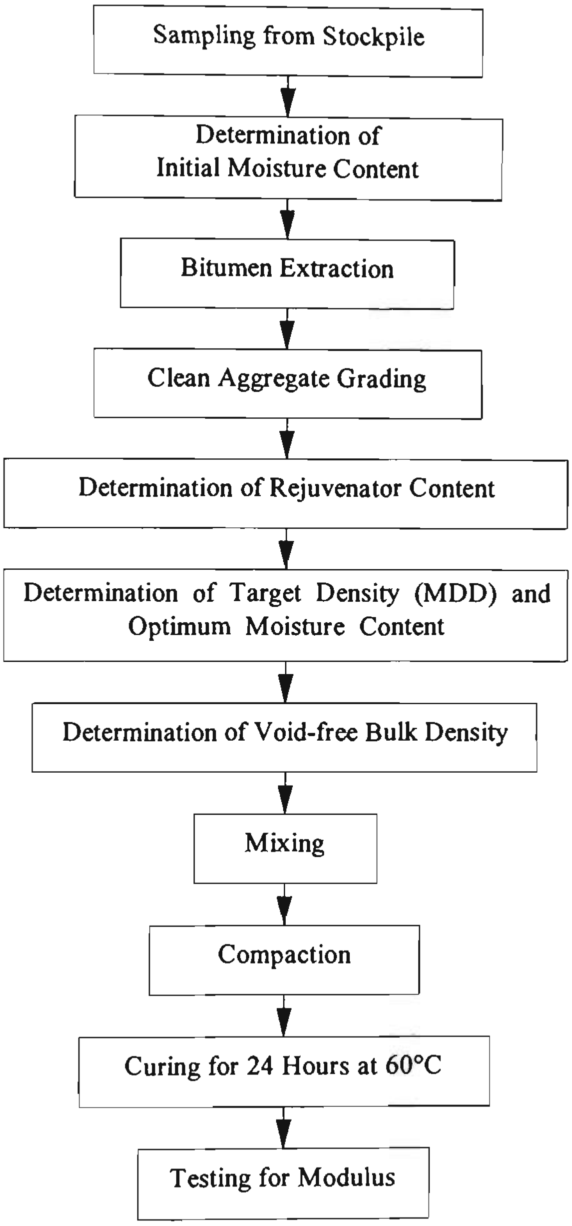

Figure 7.1 Recommended laboratory sample preparation for cold recycled asphalt

The steps depicted above are as follows:

1. Obtain a representative sample from a stockpile in accordance with AS 1141.3 (1986) or by any appropriate sampling technique.

2. Determine Initial Moisture Content of the RAP material.

3. Perform a bitumen extraction to determine the bitumen content. This determination should be done in accordance with AS 2891.3.3 (1991) or any appropriate technique or method.

4. Perform a particle size distribution analysis for the clean aggregate in accordance with AS 1141.11 (1980). If necessary, perform a sieve analysis for RAP in order to observe consistency and to identify whether the aggregate grading curve requires correction.

5. Calculate the required rejuvenator content. The Asphalt Institute equations, which use the results obtained from both the particle size distribution and the bitumen content, were used in this project. However, these may not necessarily give the optimum bitumen content. The amount of rejuvenator added will be the key to the mix stability, i.e. if too much is added, the old binder will be excessively softened and the mix will be unstable, and if too little is added, the mix will be too dry and become brittle, as there is not enough binding between particles.

6. Determine compaction density (target density), at which specimens will be compacted for testing purposes. If MDD is to be used as the target density, a modified compaction test should be done to determine the OMC which will give the MDD. The test is to be done in accordance

with AS 1289.E2.1 (1977) and the IMC and the water content in the rejuvenator agent should be taken into account.

7. Determine Void-Free Bulk Density and the bulk density at OMC to calculate the percentage voids of the compacted material at the target density.

8. Mix specimens by hand as this allows a better coating. Moisture should be added prior to the addition of the rejuvenating agent as this facilitates the mixing and blending of the rejuvenator with the RAP.

9. Compact specimens to the target density by means of a gyratory compactor. This apparatus is recommended as it permits the compaction of specimens to a given density, producing specimens with similar properties. It also minimises operator error, is less noisy, can be used on site and is easy to use and simulates field compaction by orienting particles in a similar way.

10. Cure specimens at 60°C for 24 hours. This temperature is recommended as it allows the acquisition in a short time of a modulus value which is comparable with those commonly measured on pavement cores. It is more economical than 90°C and it is a common testing temperature for bitumen testing (e.g. creep, Marshall). Also at this temperature the viscosity of the rejuvenated bitumen does not change significantly. The modulus obtained when cured for 24 hours at 60°C is thought likely to be similar to that in a pavement a few weeks after construction. Loose storage is not recommended as it did not result in any significant changes in modulus.

11. Modulus testing is recommended to be done in the MATTA as it is a non-destructive apparatus that permits the acquisition of reliable results and it complies with a draft Australian Standard AUST-001 for the determination of resilient modulus.

7.2 FURTHER RESEARCH

The following further work is recommended:

- A field trial, taking core samples to be tested for modulus, in order to determine the behaviour of the material in a pavement compared with the properties measured in the laboratory.
- The use of heated water during the mixing process. Would it accelerate the reaction between the rejuvenator and the old binder? Would this reduce the curing time of specimens cured at room temperature?
- An investigation of at what time, shorter than 24 hours, will specimens gain strength when cured at 60°C or 90°C? Would this shorter time be better for specimens cured at 90°C?
- Investigation into the best method of determining rejuvenator content.
- More viscosity testing so that its influence on modulus can be better understood.

GLOSSARY

ASPHALT:	Mechanical mixture in which bitumen is associated with inert mineral matter such as crushed rock. In the US the term refers to bitumen.
ASPHALTENES:	High molecular weight aromatic resins composed of carbon, hydrogen and some nitrogen, sulphur and oxygen.
BINDER:	A material used to hold together solid particles in a coherent mass.
BITUMEN:	A brown or black coloured material obtained by processing the residue from the distillation of crude petroleum consisting of hydrocarbons and their derivatives. It is non-volatile and softens gradually when heated.
BITUMEN HARDENING:	The tendency for bitumen to stiffen under atmospheric influences such as air and temperature.

BLEEDING:	The showing of binder on the pavement surface.
BREAKING OF EMULSION:	Separation of the two components making up the emulsion, usually a hydrocarbon and water, due to evaporation of water.
BULK DENSITY:	Mass of a unit volume of loose (uncompacted) material.
COARSE AGGREGATE:	Aggregate larger than 4.75mm.
COLD RECYCLING:	The re-use of Reclaimed Asphalt Pavement materials, including the addition of recycling agents, without the use of heat.
COMPACTION:	The reduction of volume of a material by packing its particles closer together by means of rolling, tamping or other processes.
CORE:	A cylindrical specimen drilled out of rock or pavement for testing purposes.
CURING:	The provision of an environment to facilitate the stiffening or hardening of a material.

DRY DENSITY:	The mass of a material per unit volume, without any moisture.
FINE AGGREGATE:	Aggregate smaller than 4.75mm.
GRADING:	The quantities and distribution of various particle sizes present in a mineral aggregate, expressed as a percentage of the whole.
IN-SITU:	An operation carried out on material in its final position.
MALTENES:	Low molecular weight oily medium in which asphaltene molecules are dispersed or dissolved. In bitumen, maltenes consist of the low molecular weight aromatic resins.
MOISTURE CONTENT:	Water quantity which can be removed from aggregate by heating to 105°C until constant mass is attained and is expressed as a percentage of the dry mass.
OXIDATION:	Removal of one or more electrons from an atom, ion or molecule when combined with oxygen.

OXIDATION, BITUMEN:	Removal or elimination of some hydrogen and carbon particles when hydrocarbon particles are united with oxygen.
PAVEMENT DISTRESS:	The deterioration of a pavement, which is indicated by visible surface defects.
RAVELLING:	Type of distress which consists of the loosening of stones or particles in the surface course of a pavement.
RECLAIMED ASPHALT PAVEMENT (RAP):	Removed and/or processed pavement materials that contain bitumen and mineral aggregate.
RECYCLING:	The re-use of a material after some processing or treatment so that a new material can be produced.
REPEATED LOAD INDIRECT TENSILE TEST:	Test consisting of the application of repeated load pulses to a cylindrical specimen on its side along its vertical diameter, generating an indirect horizontal tensile stress which is held for a short time, and then repeated several times.

RESILIENT MODULUS:	The measure of elastic stiffness of a material and is equal to the applied stress over recoverable strain.
RUTTING:	Pavement distress which consists of the vertical deformation of a pavement surface measured in a wheel path, relative to a straightedge placed at right angles to the traffic flow and across the wheel path.
SHOVING:	Pavement distress where lateral displacement of pavement structure in the direction of vertical travel, is produced by braking, accelerating or turning vehicles.
STABILITY OF ASPHALT:	Ability of asphalt to resist deformation under a load.
TENSILE TEST:	Determination of the strength and elasticity of a material when tested in tension.
VISCO-ELASTIC:	The combined viscous and elastic response of a material when a stress is applied.
VISCOSITY:	Ratio of the magnitude of an applied shear stress to the velocity gradient which the stress produces.

WORKABILITY:	Property of a material determining the ease with which it can be placed in position and compacted.

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APPENDIX A

TESTS AND PROCEDURES COMMONLY PERFORMED ON RECYCLED ASPHALT

- **Centrifuge Kerosene Equivalent**
- **Coating Test**
- **Fatigue Test**
- **Gyratory Shear Compactor**
- **Hveem Stability and Cohesion**
- **Kneading Compaction**
- **Marshall Test**
- **Penetration**
- **Recovery of Bitumen by Abson Method**
- **Repeated Load Indirect Test**
- **Resilient Modulus**
- **Vacuum Saturation**
- **Viscosity**

TESTS AND PROCEDURES COMMONLY PERFORMED ON RECYCLED ASPHALT

CENTRIFUGE KEROSENE EQUIVALENT (CKE)

The CKE is used as part of the Hveem procedure for bituminous mixes to determine the Approximate Bitumen Ratio (ABR) and the bitumen content. The CKE test consists of saturating with kerosene a dry sample (100g) of the material passing the 4.75mm sieve. The saturated sample is placed in a centrifuge at a force of 400 times gravity for 2 minutes, after which the sample is re-weighed to determine the amount of kerosene retained (absorbed) by the aggregate. This is done by subtracting the original sample mass (100g) from the saturated centrifuged sample mass. The difference in mass is called the CKE and is expressed as a percentage (The Asphalt Handbook, 1988 and ASTM D 5148-90).

COATING TEST

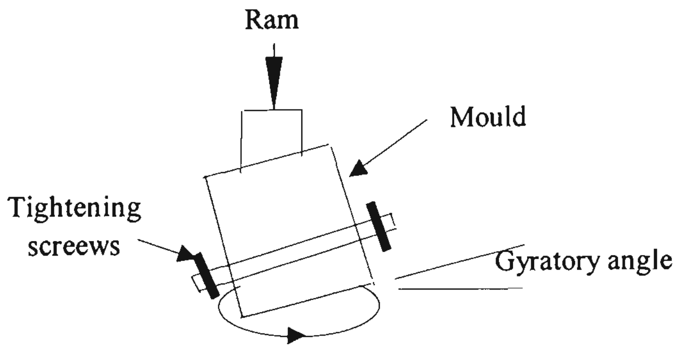
A coating test is performed to determine the adhesion between bitumen and aggregate when water is also present. The test consists of immersing a tray of bitumen in water for a specified length of time. The clean aggregate is then pressed into the surface of the bitumen while still submerged in water. The tray is removed from the water. The water is drained off and the aggregate is removed. The adhesion of bitumen to the aggregate is then assessed by visually estimating the amount of bitumen attached to the stone (Whiteoak, 1990).

FATIGUE TEST

The fatigue test is carried out under uniaxial conditions by direct loading. The test consists of applying to a specimen (200mm long by 40mm wide and 30mm deep), a load as an alternating stress or strain. This load is repeatedly applied at the mid point of the specimen. The number of load applications required to produce failure is then determined. In this test, failure is determined by a reduction of 50% of the load required to maintain a strain level (Whiteoak, 1990).

GYRATORY SHEAR COMPACTION (GSC)

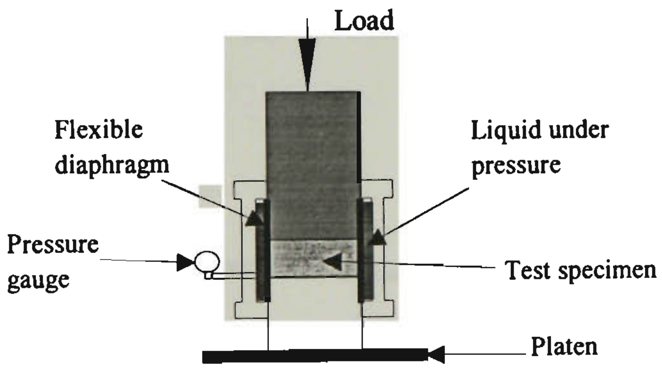
The apparatus employs a gyratory shearing action at a low pressure in order to orientate the aggregate particles to aid compaction. The shearing action is applied under a constant normal stress, bringing the particles close together. The normal stress is applied by compressing the aggregate particles in a cylindrical mould between top and bottom plates. The gyratory movement of the mould creates the required shear throughout the test. Specimens are compacted under constant pressure and speed and a fixed gyratory angle to specifications (normally between 2° to 4°). The figure below shows the GSC principle.



GYRATORY COMPACTOR

HVEEM STABILITY AND COHESION

Hveem Stability or resistance to plastic deformation of a compacted specimen, is determined by means of the Hveem stabilometer. The resistance to deformation of 'early cured' specimens is defined as the R-value and, the stability of 'fully cured' specimens is defined as the S-value. The stabilometer is a form of a triaxial test that uses cylindrical specimens of 102mm in diameter and 64mm in height. The cylindrical specimen is confined in a rubber sleeve which is surrounded by liquid in a sealed steel cell. The specimen is loaded by a plunger in a compression test machine set to travel at a rate of 1.3mm/min. At loads of 13.4, 22.3 and 26.7kN, the pressure developed in the surrounding liquid is recorded. The figure below shows the components of the Hveem Stabilometer.



HVEEM STABILOMETER

The stabilometer value S is then calculated from:

$$S = \frac{22.2}{\frac{(P_h \times D)}{(P_v \times P_h)} + 0.222}$$

where:

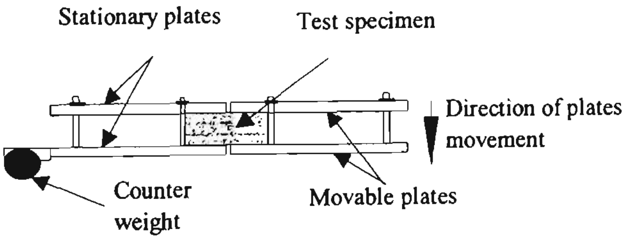
P_h = lateral pressure corresponding to Pv

D = displacement of specimen

Pv = vertical pressure, typically that due to the 22.3kN load.

(The Asphalt Handbook, 1988 and ASTM D 1560-81a).

The cohesion of a compacted specimen is determined by means of the Hveem cohesiometer and consists of the measurement of a force required to break or bend a cantilever beam specimen. The figure below shows the components of the Hveem cohesiometer. The specimen is of cylindrical shape with dimensions 102mm in diameter and 64mm in height. The test is performed in a controlled temperature cabinet at 60°C. The specimen is placed between 2 stationary plates and 2 movable plates parallel to the specimen surface. The movable plates deflect from horizontal when a load is applied at a rate of 1800g/min (18kN/min) to the end of a rod attached to the movable plates. The test is stopped when a certain deformation is reached or the specimen breaks. The force at breaking is recorded.



HVEEM COHESIOMETER

The cohesiometer value C is calculated from:

$$C = \frac{L}{W(0.020 \times H + 0.0044 \times H^2)}$$

where:

L = mass of shot (g)
W = specimen width (cm)
H = specimen height (cm).

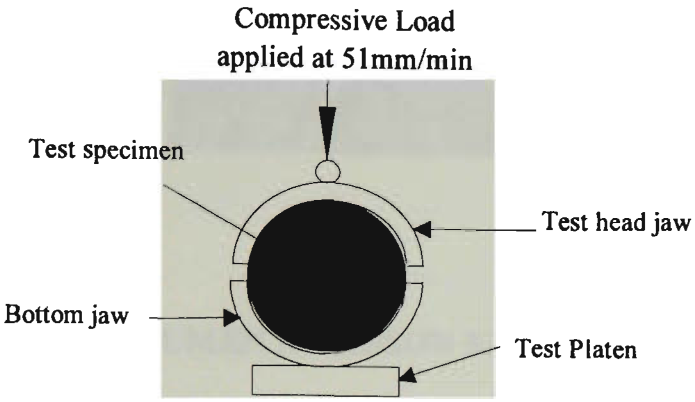
KNEADING COMPACTION

The kneading compactor is a mechanical device that imparts to the specimen a series of individual impressions made with a ram in a kneading action. The ram has the shape of a sector and has an area of 3.1in^2 (20.06cm^2). The test is performed under controlled temperature. The specimens are initially semi-compacted by applying 20 blows at a pressure of 1.7MPa. This is done to condition the specimen so that it will not be disturbed when the full pressure is applied. After semi-compaction, the compacting pressure is increased to a final 3.4MPa applying 150 blows (ASTM D 1561-81a).

MARSHALL TEST

The Marshall test is used to determine the Marshall stability of a compacted specimen and the total deformation. The specimens are compacted by applying 50 or 75 blows on each face with a 4.54kg hammer dropping a height of 457mm (ASTM D 1559-82).

The Marshall test is performed at 60°C in an unconfined-compression apparatus, where a compacted cylindrical specimen 102mm in diameter and 64mm in height is compressed across a diameter in a special test head at a constant compression rate of 51mm/min. The load at which the specimen fails is known as stability and the deformation produced is known as flow. The figure below depicts the main components of the Marshall apparatus.

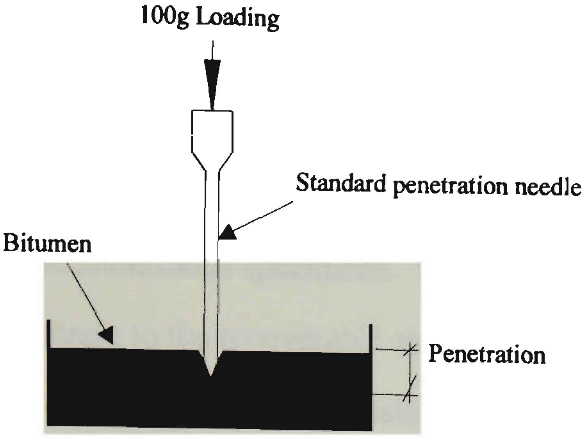


MARSHALL TEST

PENETRATION

The penetration test is used to measure the flow properties of a bituminous material. Penetration is measured by the penetrometer and the higher the penetration value the softer is the material. Penetration is expressed as the distance in tenths of a millimetre that a standard needle vertically penetrates a bituminous sample under known conditions of loading(100g), time (5 seconds) and temperature(25°C) (Whiteoak, 1990 and ASTM D5-86).

The sample is softened at a temperature not higher than 90°C for no longer than 30 minutes so that a uniform uniform surface is obtained. The sample depth should be at least 10mm greater than the expected needle penetration. The sample is left to cool at room temperature for 1 to 2 hours. Three or four penetrations are made and the average value is reported. The following figure depicts the penetration test.



RECOVERY OF BITUMEN BY ABSON METHOD

The test consist of the distillation of a solution of solvent and bitumen from a bitumen extraction. The distillation is conducted under specified conditions (ASTM D 1856-79) to a point where all solvent has been distilled. The test is done under carbon dioxide gas to stop the bitumen from hardening and oxidising until all traces of the solvent are removed. The recovered bitumen is used for viscosity and penetration testing as it has similar properties to those of the original material.

REPEATED LOAD INDIRECT TENSILE TEST

This test is used to determine the elastic stiffness of laboratory compacted specimens or field sampled specimens. The test consists of applying repetitive vertical load pulses to a Marshall cylindrical specimen across its diameter through loading platens parallel to the central axis. Horizontal strains across a diameter are measured by lateral transducers placed on the specimen and which are connected to a computer.

RESILIENT MODULUS

The resilient modulus test is one of the most important parameter obtained from the RLITT performed on bituminous specimens. Resilient modulus is defined as the ratio of the applied stress to the recoverable strain when a load is applied and removed (Noureldin and Wood, 1990). The resilient modulus is obtained in the laboratory by applying a pulsating load across the vertical diameter of a Marshall size specimen (diametral compression mode), and measuring the horizontal deformation across a diameter.

VACUUM SATURATION

The aim of vacuum saturation is to bring laboratory specimens to their lowest mechanical strength in order to produce moisture damage equal to that occurring in pavements. The test simulates the effects of prolonged exposure to surface water and consists in placing specimens in a vacuum chamber filled with water and applying a vacuum of 100mm mercury for one hour. When the vacuum is released, the specimen remains submerged for a further one hour. The specimen is removed and surface dried and weighed. The specimen is then used in Marshall and/or Hveem testing (Terrel and Fritchen 1978; Asphalt Cold Mix Manual 1989).

VISCOSITY

Viscosity of bitumen is used to determine its flow properties at a given temperature. The basic unit of viscosity is Pascal seconds and is obtained by dividing the applied shear stress by the shear rate per second (Whiteoak, 1990).

There are two types of viscosity measurements, the absolute or dynamic viscosity and the kinematic viscosity. Absolute viscosity is measured in Pascal seconds (Pa.s) using the sliding plate viscometer. This apparatus consists of 2 flat parallel glass plates with a thin film of bitumen in between. The thin film is subjected to a known shear stress in Pascal. The shear rate in seconds is determined and viscosity is then calculated. This test is described in Appendix C.

Kinematic viscosity is measured in square millimetre per second (mm^2/s), which is equivalent to a centistroke (cSt) using a capillary tube viscometer. The test consists of a glass tube through which bitumen flows. The glass tube has narrower and wider parts with various marks to indicate the volume or flow of the bitumen. Viscosity is then measured by timing the flow of a fixed quantity of bitumen through the glass tube at a given temperature.

APPENDIX B

MIX DESIGN PROCEDURES, SAMPLING AND TESTING TECHNIQUES

- **State of California**
- **State of Pennsylvania**
- **State of Oregon**
- **Purdue University, Indiana**
- **Chevron USA Inc**
- **Asphalt Institute**
- **State of Texas**
- **Witco Corporation**
- **Israel**
- **Ontario Canada**

1. STATE OF CALIFORNIA

The mix design method used by the state of California Department of Transportation and reported by Epps (1990) consists of determining the percentage and grade of recycling agent to use. To do so, samples are obtained from the pavement to be recycled by either pavement coring, or taking large excavated pieces which are then crushed in the laboratory. The RAP material is evaluated by determining the bitumen content (P_b), aggregate grading and viscosity of bitumen recovered by the Abson recovery method. The addition of new aggregate for the correction of grading is not mentioned in this method. Following bitumen extraction, surface area of the aggregate is found in order to determine the Approximate Bitumen Requirement (ABR). This is done using the equation:

$$ABR = \frac{4R + 7S + 12F}{100} \times 1.1$$

where:

R = percentage retained on the 2.36 mm sieve

S = percentage passing the 2.36 mm sieve and retained on the 75 μm sieve

F = percentage passing the 75 μm sieve.

Therefore, the amount of recycling agent required equals the ABR minus P_b. The grade or type of recycling agent is determined by means of the viscosity of the RAP, using a nomograph which contains the viscosity of different recycling agent bases. At the point where the RAP viscosity meets with a recycling agent base, it will indicate the recycling agent to use for testing.

Six RAP specimens are used for testing, of which one is used to determine the specific gravity of RAP (according to ASTM D 2041). Four specimens are dried to constant mass, and 2% water is added, after which they are mixed to different emulsion contents starting at the calculated amount (ARB-P_b). The last specimen is kept as a spare. The mixed specimens are cured loose at 60°C for 16 hr ± 1 hr and compacted with a kneading compactor at 60°C. After compaction, Hveem stability at 60°C is measured and percentage air voids is calculated. These values are used to recommend the Optimum Bitumen (Binder) Content to use in the mix.

The bitumen content recommended by California is that which will not show any evidence of surface flushing or bleeding on the compacted specimen and which will give a minimum of 4% air voids.

2. STATE OF PENNSYLVANIA

The Pennsylvania mix design method as presented by Epps (1990) is based on the results of resilient modulus tests on cores taken from RAP projects. The Marshall test is performed, but results are used for information only.

Pavement cores (15) obtained from the field, or bags (5) of material obtained from stockpiles, are crushed in the laboratory. In this method, layer thickness of the pavement, the type of the pavement problem, and aggregate type, are documented.

The Abson recovery method is performed on at least three specimens, to recover bitumen for rheological tests. Aggregate grading, bitumen viscosity at 60°C (140°F), and penetration at 25°C (77°F) are also obtained from at least three specimens. Up to 50% of new aggregate may be used to adjust the RAP grading.

The binder content is determined by the binder demand of the RAP aggregate after extraction of bitumen, and is calculated by means of the aggregate surface area formulae used by Chevron USA Inc, The Asphalt Institute, Witco Chemicals and the state of Illinois. The results obtained are used to establish the range of binder content to be used in the mixing process.

Optimum moisture content is first determined for the material, starting at 3%, with increments of 1% and using a constant binder (emulsion) content at 2.5% by weight of RAP. The mixing is done by hand for approximately two minutes at room temperature and with the binder heated at 60°C.

The optimum emulsion/binder content is determined using three mixtures at four emulsion contents (2%, 2.5%, 3% and 3.5%) and the established optimum moisture content. The amount of binder added to the RAP depends on the percentage of RAP used, the bitumen content present in the RAP, and whether new aggregate that has been used, in which case a higher binder content is added. The added binder grade or type is selected depending on the extracted bitumen penetration and viscosity.

Specimens are cured in an oven at 40°C (104°F) for 45 minutes, and then remixed for 30 seconds before compaction after measuring the percentage moisture loss. Compaction is performed at 23°C (73°F) using a Marshall hammer applying 75 blows on each face. The compacted specimens are then cured in the moulds at 23°C for 15 to 24 hours before being extruded. The extruded samples are further cured for 3 days at 40°C (104°F). After this curing process, specimens are used to determine initial resilient modulus at 25°C (77°F). Immediately after testing, specimens are vacuum saturated and soaked in water for 30 minutes at 25°C. Soaked resilient modulus, Marshall stability and flow values and bulk specific gravity are then determined. The optimum binder content is then selected by considering the bulk specific gravity, initial resilient modulus, soaked resilient modulus and percent-retained resilient modulus[1].

Tests performed by the state of Pennsylvania showed that initial resilient modulus decreased as emulsion content was increased. The optimum binder content is established by the rate of decrease of resilient modulus after vacuum saturation i.e. percent retained resilient modulus.

3. STATE OF OREGON

The Oregon procedure for mix design is presented in Rogge *et al.* (1992), Epps (1990) and Hicks *et al.* (1989). Samples obtained from the field are reduced by crushing to 100% passing the 25mm sieve.

Tests performed on the RAP are:

1. Bitumen content in percentage, and aggregate grading.
2. Penetration at 25°C of Abson recovered bitumen.
3. Absolute viscosity at 60°C of Abson recovered bitumen.
4. Grading of the RAP using 12.5mm, 6.3mm and 2.0mm (No 10) sieves.

The emulsion content of RAP is estimated using absolute viscosity and penetration values on charts developed from values obtained in previous Cold In Place Recycling projects or by the following formula:

$$EC_{EST} = 1.2 + A_G + A_{A/C} + A_{P/V}$$

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[1] Percent-retained resilient modulus equals the initial resilient modulus minus the soaked resilient modulus.

where:

1.2 = Base emulsion Content

EC_{EST} = Estimated emulsion content, in percent

A_G = Adjustment for grading, in percent

$A_{A/C}$ = Adjustment for bitumen content, in percent

$A_{P/V}$ = Adjustment for penetration or viscosity, in percent.

A_G, $A_{A/C}$, and $A_{P/V}$, are obtained from a chart produced from previous experience. These adjustments are determined by using the results obtained from grading of RAP, viscosity, penetration and bitumen content of the old binder.

The Design Emulsion Content is determined by trial and error using the chart and the above formula, with a starting point of 1.2% by dry weight of RAP, and can be increased or decreased depending on its consistency and achieved properties. The estimated emulsion content can be as low as 0.6% and as high as 1.8%.

Specimens for Hveem Stability and resilient modulus are prepared in the laboratory at the estimated design emulsion content and at water contents of 0.5%, 1.0% and 1.5%. The material is placed in moulds and compacted by kneading compactor. The preparation procedure of specimens consists of adding the desired amount of water and hand mixing together with the emulsion. The emulsion is preheated at 60°C for one hour.

The mixed material is placed in a pan and cured for one hour at 60°C. The material is then placed in Marshall moulds and compacted at 60°C using 50 blows. The compacted material is cured overnight at 60°C in the moulds and is re-compacted in the kneading compactor. Before extrusion, samples are further cured at 60°C for 24 hours. After extrusion, the specimens are cured for 72 hours at room temperature prior to being tested for Hveem stability and resilient modulus at room temperature.

The emulsion content is recorded at the peak value of Hveem S-value and resilient modulus, and is checked with the estimated emulsion content previously calculated, EC_{EST}. The selection of the final estimated emulsion content is based on the laboratory results, allowing for field adjustments.

Field adjustments to the estimated emulsion content are made considering the RAP grading, moisture content, and pavement condition. The corrections for pavement conditions are, for fat spots 0.2% emulsion content reduction, unstable or rutted areas 0.4% emulsion content reduction. For visual appearance after compaction an adjustment of 0.1% to 0.2% may be made. If the pavement ravels and has a brown colour, emulsion is added, and if the pavement is black and shiny with no ravelling, it is reduced.

4. PURDUE UNIVERSITY, INDIANA

The recommended mix design procedure was developed from a study done by Tia *et al* (1983). The procedure starts with the evaluation of the new aggregate and reclaimed asphalt gradings. Resilient modulus, Hveem R-values and Marshall stability and flow are used to determine the properties of the material.

The bitumen content of the reclaimed material is determined. The grading is performed on the clean aggregate and the addition of new aggregate is determined from it. Aggregate is added to produce a grading meeting the Indiana specification limits. The specimens are then mechanically mixed for two minutes, followed by half a minute hand mixing, using the optimum amount of rejuvenating agent as determined by a gyratory compactor machine.

Specimens are compacted using one of two compactive efforts - either 1400kPa (200psi) at 20 revolutions or 1400kPa at 60 revolutions. After compaction, specimens are cured in the moulds for 24 hours at room temperature (22.2°C (72°F)) or at 60°C, depending on the compactive effort used. At the end of the compaction period, unit weight, resilient modulus, Hveem R-value and Marshall stability and flow are determined in that order.

5. CHEVRON USA INC.

To determine the optimum binder content, the Chevron USA Inc. method uses the resilient modulus, Hveem Stabilometer, cohesiometer, and mix workability as presented in Epps (1990) and also in Santucci and Hayashida (1983).

The RAP is evaluated by bitumen content, aggregate grading and either viscosity at 60°C, or penetration at 25°C and viscosity at 135°C, whichever is appropriate. New aggregate is added only if an adjustment in the grading of RAP is required, or to increase the amount of emulsified agent in the mix. To determine the amount of recycling agent required, binder demand is determined using one of two methods -the Centrifuge Kerosene Equivalent (CKE) or the aggregate surface area formula (as in the California method). Then the amount of recycling agent equals binder demand of the recycled mixture minus bitumen content of RAP. The percentage of emulsified recycling agent required is based on weight of aggregate as follows:

$$P_c = \frac{PR - (P_a \times P_p)}{R}$$

where:

P_c = Percentage emulsified agent (Recycling Agent Content)

PR = Percentage binder demand by CKE

P_a = Percentage bitumen in reclaimed asphalt

P_p = Percentage reclaimed asphalt pavement in Recycled mix

R = Percentage emulsion residual (60%-65%)[2].

Not less than 2% emulsified recycling agent should be used. If P_c results in less than 2%, additional untreated aggregate should be added and the binder demand is recalculated. Chevron Inc. has created a table as a guide for selecting the emulsified bitumen or recycling agent using the results from viscosity and/or penetration.

Trial mixes are prepared in the laboratory at different Recycling Agent Contents (RAC), including: 1% below the estimated RAC, at the estimated RAC, and 1% and 2% above the estimated RAC.

Testing starts with a coating test to asses the how easily the binder adheres to the stone, followed by compaction using a kneading compactor applying 30 blows on each face, and followed by a 178kN static load using a double plunger method at 22.8°C (73°F). Hveem resistance and cohesion and resilient modulus are obtained after initial and final curing and water soaked curing conditions are met. Initial curing is done in the mould for a total of 24 hours at 22.8°C ±1°C. Final curing is performed in the mould for a total of 72 hours at 22.8°C ±1°C

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[2] Emulsions consist of a percentage of water and a percentage of a residual. Water contents are usually between 35% and 40%.

followed by 4 days vacuum desiccation at 10 - 20mm mercury. Water soaked curing is performed under vacuum saturation at 100mm of mercury for 24 hours.

The job mix formula is then established by the lowest emulsified recycling agent content (with 2% minimum) that meets all the following criteria:

- Resilient modulus after final curing: 150,000-600,000psi (1.04 - 4.1MPa)
- Stabilometer 30 minimum at 60°C
- Cohesiometer 100 minimum at 60°C.

6. THE ASPHALT INSTITUTE

The Asphalt Institute Method starts with surface area calculations to determine the binder content. These calculations are done using a series of formulae which are defined later. Samples are obtained randomly from the field using sampling techniques described in the Asphalt Institute Manual No 21 (1983). Bitumen content and aggregate grading of the RAP are determined. New aggregate is only added to correct RAP aggregate grading and/or to increase the thickness of the recycled pavement.

The selection of the emulsifying agent depends on the type of problem present in the pavement to be recycled and the engineering properties of the bitumen. The binder demand in the recycled mixture is determined using an aggregate surface area formula. The recycled cold-mix design recommended by the Asphalt Institute consists of the following steps:

1. Determination of grading and bitumen content of RAP.
2. Determination of grading of clean aggregate in RAP, and amount of new aggregate if required.

3. Calculation of combined aggregate in recycled mix to meet specification requirements, using the grading of the RAP material, the reclaimed aggregate and new aggregate.
4. Selection of type and grade of new binder.
5. Determination of binder demand of combined aggregates using the following formula:

$$P_c = \frac{0.035a + 0.045b + Kc + F}{R}$$

where:

P_c = Percentage of bitumen material by weight of total mix

K = 0.15 for 11 - 15% passing 75μm sieve

0.18 for 6 - 10% passing 75μm sieve

0.20 for 5% or less passing 75μm sieve

a = Percent of mineral aggregate retained on 2.36mm sieve

b = Percent of mineral aggregate passing 2.36mm sieve and retained on 75μm sieve

c = Percent of mineral aggregate passing 75μm sieve

F = 0 to 2.0% (depending on absorption of aggregate)

R = 1.0 for asphalt cement

0.60 to 0.65 for bitumen emulsions.

6. The new binder to be added equals the calculated binder demand minus bitumen content in RAP and is calculated by:

$$P_r = P_c - \frac{(P_a \times P_p)}{R}$$

where:

P_r = Percent new binder in recycled mix

P_c = Percent of binder by weight of total mix

P_a = Percent of bitumen in reclaimed asphalt pavement

P_p = Percent reclaimed asphalt pavement in recycled mix

R = 1.0 for asphalt cement in reclaimed pavement
0.60 to 0.65 for emulsified bitumen
0.70 to 0.80 for cutback bitumen.

7. Adjustment of bitumen content by field mix trials. This is made by the field engineer and is done to minimise deformation and cracking.

7. STATE OF TEXAS

The method used for the preparation of recycled mixes (requested by the Texas Department of Highways and Transportation), and reported by Kennedy and Perez (1978), uses the results obtained from both static and repeated-load indirect tension tests to determine estimates of fatigue and resilient properties. The specimens used are sampled from different projects and divided into laboratory prepared specimens, cores and field mixed specimens.

This method results from a study done by Kennedy and Perez, and it is not known whether the method has become an official practice. The process followed by Kennedy and Perez consisted of:

1. *General Design:* To determine the properties of RAP. The steps followed are:
   a. Determination of aggregate grading.

b. Determination of bitumen content.

c. Determination of final grading after addition of new aggregate if required.

2. *Preliminary Design:* To select the types and amounts of additives which will soften the existing binder and reduce its viscosity or increase its penetration until it reaches the specified or desired range. The steps followed were:

   a. Extraction and recovery of bitumen by the Abson method.

   b. Mixing extracted binder with different types and amounts of additives to measure viscosity or penetration of the treated binder.

   c. Selection of combinations which produced a binder of a desired consistency i.e. viscosity and penetration.

3. *Final Design:* To determine the amount of additive required and whether the engineering properties of RAP were acceptable. The steps were as follows:

   a. Preparation of mixes containing different binder percentages and tested according to the Texas Department of Highways and Transportation standards. The aggregate and binder were heated and mixed together for approximately three minutes. Field mixed specimens were sampled from the plant and reheated before compaction. The mixtures were placed in an oven to reach testing temperature and later compacted using a Texas gyratory shear compactor.

   b. Specimens were tested using the static test procedure to determine tensile and static elastic properties of RAP. The repeated-load indirect tensile test was used to determine fatigue. The test was carried out at 24°C and was continued until the specimen reached failure, ie. specimen was fractured.

   c. Test results were compared with those of conventional asphalt mixes.

8. WITCO CORPORATION

The Witco Corporation method for mix design consists of preparing a laboratory mix that will meet minimum stability requirements of Marshall and Hveem test procedures. The mix is designed by following the three steps stated by Escobar (1992) which are as follows:

Step One: Basic properties of RAP, such as bitumen content, aggregate grading, bitumen cement consistency and binder demand of the aggregate, are determined.

A representative sample of about 10kg is heated in an oven at 60°C for about one hour, and is then broken up by hand. A 2kg portion is used to determine the bitumen content, using a suitable solvent. The consistency of the recovered bitumen is determined by either penetration at 25°C or viscosity at 60°C. The grading of the dried aggregate is used to determine the binder demand by either the Centrifuge Kerosene Equivalent (CKE) or by the following formula:

$$P = \frac{(4R + 7S + 12F)}{100} \times C$$

where:

P = percentage weight of binder in the mix

R = percentage weight of rock in the aggregate, retained on 2.38mm sieve

S = percentage weight of sand retained on 75μm

F = percentage weight of fines in the aggregate, passing 75μm

C = factor (normally 1.0 for new aggregate and up to 1.2 if the extracted bitumen is very hard i.e. if penetration at 25°C is 1.0mm or less).

Note that the formula is not stated correctly in Escobar (1992).

The minimum amount of recycled agent to be added is equal to the calculated binder demand minus the bitumen content of the RAP.

Step Two: The selected recycling agent should produce a durable and workable mix. To select the recycling agent to use, five basic components of the bitumen governing its behaviour should be identified. These are: Asphaltenes(A), Nitrogen Bases (N), first acidaffins (A_1), second acidaffins(A_2) and paraffins(P).

Step Three: This step consists of analysing the data for the design of the mix. The Witco corporation has developed nomographs to predict the results to be expected from this method. This will indicate whether or not the amount of recycling agent in the recycled pavement will produce the desired consistency.

After completing the three steps, specimens are then prepared for Marshall and Hveem tests to determine if the estimated design mixes meet the minimum stability requirements. If these are not met, the concentration and/or grade of recycling agent is adjusted as necessary.

9. **Israel**

The laboratory mix design for cold recycled asphalt presented by Cohen *et al* (1989), has steps similar to those used in Illinois, except for modifications made to satisfy warm weather conditions. The procedure consists of the following steps:

i) Determining the thickness and type of material present in the reclaimed asphalt layer.

ii) Selection of the amount and grading of new aggregate to be added by means of a sieve analysis.

iii) Bitumen extraction and determination of its properties (penetration and ductility).

iv) Determination of the amount of binder/rejuvenator needed and the selection of its type and grade.

Test specimens consisting of a blend of 70% reclaimed material, 20% virgin aggregate and 10% quarry sand are prepared at four emulsified recycling agent contents, these being 4, 5, 6, and 7% by weight of dry aggregate. The preparation of samples is as follows:

1. About 4kg of cold recycled mix is prepared to manufacture three specimens for each emulsified agent content.
2. An initial moisture content of 1% is used to improve mixture workability and aggregate coating. The mix is left to stand for 10 minutes at room temperature to let water fill surface voids and to obtain a uniform coating of mixture over the aggregate.
3. The cold emulsified recycling agent is added to the wet mix and mixed by hand for 1 minute.
4. The specimens are compacted with a Marshall compaction hammer using 75 blows on each side of the specimen.
5. Specimens are cured for 16 hours at 60°C in a forced draft oven to ensure a reaction between rejuvenating agent and old binder, and ensure curing of the recycling agent in the mix.
6. The specimens are left to cure in the moulds for 3 and 10 days at a room temperature of 22°C before testing.

The cored specimens are analysed by tests such as:

1. Strength tests on cores using the Marshall stability method to obtain information on cracking, rutting or deformation.
2. Durability tests to predict the pavement service life after continuous and combined water and temperature damaging effects. The tests used are the Marshall immersion and capillarity soaking.
3. Non Destructive Test (NDT) to determine the structural capacity of the pavement.

10. ONTARIO, CANADA

The preparation procedure for Cold In-Place recycling used in Ontario and described in Emery (1993) is based on practical experience from other projects. The starting point for the characterisation of representative samples of the old pavement is the recovery of bitumen, and is finished by testing the bitumen to ensure it complies with specifications. The procedure consists of four sections which are:

A. *Properties determination of representative samples.*

Specimens are obtained from millings or from coring. These specimens are used to determine moisture content, bitumen content, grading and penetration.

B. *Specimen preparation.*

Five specimens are prepared for five different binder/emulsion contents (0.5%, 1.0%, 1.5%, 2.0% and 2.5%). Specimens are mixed to the estimated field moisture content and with the warm emulsion (heated at 60°C). These are later loose-cured in a pan at 60°C for one hour and then compacted in Marshall moulds using 50 blows on each face, followed by overnight curing in the moulds at 60°C. These are then re-compacted using 25 blows on each face. The re-compacted specimens are further cured in the moulds on their side for 24 hours at 60°C prior to extrusion. Specimens are then allowed to cool to room temperature before testing.

C. *Testing.*

From each group of specimens at the same emulsion content, one is used to determine maximum density and four are used to determine the bulk density to determine air voids. From these four, two are used to determine Marshall stability and flow at 22°C, and two at 60°C to determine the Optimum Emulsion Content.

D. *Selection of Optimum Emulsion Content (OEC).*

The OEC is obtained from the plots of density, air voids, stability at both 22°C and 60°C versus percentage added emulsion. The results obtained should be:

* Stability at 22°C of not less than 8900N, and at 60°C not less than 4500N;
* air voids between 8 and 12%, and
* specimens should show adequate coating.

APPENDIX C

DESCRIPTION OF PREPARATION AND TESTING PROCEDURES AND TESTING APPARATUS USED IN THE RESEARCH

- **Crushing Process**
- **Void-Free Bulk Density Test**
- **Compaction Test Procedure**
- **Resilient Modulus Testing**
- **Viscosity of Bitumen in RAP**

DESCRIPTION OF PREPARATION AND TESTING PROCEDURES AND TESTING APPARATUS USED IN THE RESEARCH

CRUSHING PROCESS

RAP material was crushed as follows:

1. When the material to be recycled is brought into the plant, it is assessed at the weighbridge to record the weight and origin of the material. The material is then unloaded at a specific stockpile.

2. At the time of crushing, the material is collected from the stockpile using a front-end loader and fed from a vibrating base into the primary jaw crusher, so that large pieces of RAP are reduced to manageable sizes. The crushing of RAP requires a longer period of time than that required to crush concrete or virgin aggregate, because the bitumen covering the stones is visco-elastic and does not shatter like concrete.

3. The crushed RAP material is transported on conveyor belts, with sprinklers located above the belts to wet the material to reduce loss of fines. It passes under a self cleaning electromagnet which removes any steel present in the RAP material.

4. RAP then passes onto another conveyor which carries it into the picking station where unsuitable materials such as plastic, timber, or roots from plants are manually removed.

5. The conveyor belt then carries the material to a triple-deck vibrating screen, where material passing the 20mm screen is sent to the production stockpile on another conveyor The retained material is placed onto a separate conveyor belt and carried to an impactor where it is again crushed (secondary crushing). If some steel is still present, it is removed at this point by a magnet.

6. The crushed product is transported back from the secondary crusher to the triple deck vibrating screen for further screening. Step 5 is repeated until the material is crushed to the required size (20mm). Then it is stockpiled ready for sampling and use.

VOID-FREE BULK DENSITY TEST

The test consists of placing a sample of RAP of approximately 1.5kg in a pycnometer (2L glass flask). Prior to the test, the pycnometer and its lid, a glass plate slightly larger than the top of the pycnometer, were weighed.

The mass of the pycnometer with sample and lid was recorded and, later, warm water (35°C to 38°C) was added until it reached 50mm above the sample. The pycnometer was placed under vacuum to remove any air present and was periodically agitated to remove any bubbles. Once all air had been removed, the vacuum was slowly released and the pycnometer was filled with warm water.

The pycnometer was placed in a water bath at a temperature of 25°C ± 1°C for 1 hour or until constant temperature was reached. Once the temperature was reached, the pycnometer was topped up with water and the lid was slid on making sure no air bubbles were trapped underneath the lid. The pycnometer was inverted by hand several times to observe for any air bubbles. If air bubbles were present, the lid was removed and the pycnometer was topped up with water, covered with the lid and inverted several times until air bubbles were eliminated. When this was achieved, the pycnometer was dried and weighed. The Void Free Bulk Density (VFBD) was computed using the following equation:

$$\mathrm{VFBD} = \frac{(m_2 - m_1)}{(m_2 - m_1) - (m_3 - m_4)} \times \rho_w \qquad (4.5)$$

where:

m_1 = mass of pycnometer and lid (g)

m_2 = mass of pycnometer, lid and sample (g)

m_3 = mass of pycnometer, sample, water at 25°C, lid and no air bubbles (g)

m_4 = calibrated mass of pycnometer full of water at 25°C and lid (g)

ρ_w = density of water at 25°C ($0.997044 g/cm^3$).

COMPACTION TEST PROCEDURE

The compaction test was performed in the following sequence:

1. The cylindrical mould of 100mm in diameter was prepared by putting a bottom plate into the mould, followed by a 1mm thick by 100mm diameter stainless steel disc. This assembly was then placed on a scale to determine the tare mass.

2. The calculated amount of the prepared RAP material was poured into the cylinder, making sure all material was poured evenly in order to avoid

segregation. Large stones accumulating on the top surface result in a large number of cycles during compaction. If they accumulate around the sides of the mould large voids can result, which make the specimens more fragile and easily broken when handled. Another stainless steel disc of the same dimensions as the first was placed on top together with a wooden spacer disc, which was used to produce specimens 65mm in height.

3. All the parameters required to compact the RAP sample were entered into the control unit of the machine, and were as follows:
    i) Test Number (I) or identification number.
    ii) Sample Mass (m) in grams. This is the total mass of RAP placed in the mould.
    iii) Working Pressure (p) in bar. Six bar (600kPa) was used in the compaction of the specimens.
    iv) Length of Test (M) in cycles. The maximum number of cycles was 400 since specimens were to be compacted to a target density.
    v) Density Limit (d) in kg/m^3. The target bulk density to which specimens were to be compacted.

4. The cylinder was then fastened in place into the ICT device. All the information given to the control unit was checked and the test was then started.

5. The test commenced when the piston ran down applying the working pressure on the sample. The motor started and the number of cycles were counted automatically by the control unit. The density achieved was displayed after 5, 10, 20, 40, 81, and 161 cycles.

6. When the target density was obtained, the machine stopped automatically. At this stage, the data was recorded and a brief report was printed showing the date and time of the test, the test number, sample age, sample weight and the work pressure used. The print-out also showed the number of cycles and the density reached. It concluded with the final density obtained and the number of cycles required to reach it. Figure 4.4 depicts the ICT apparatus and its compaction mould.

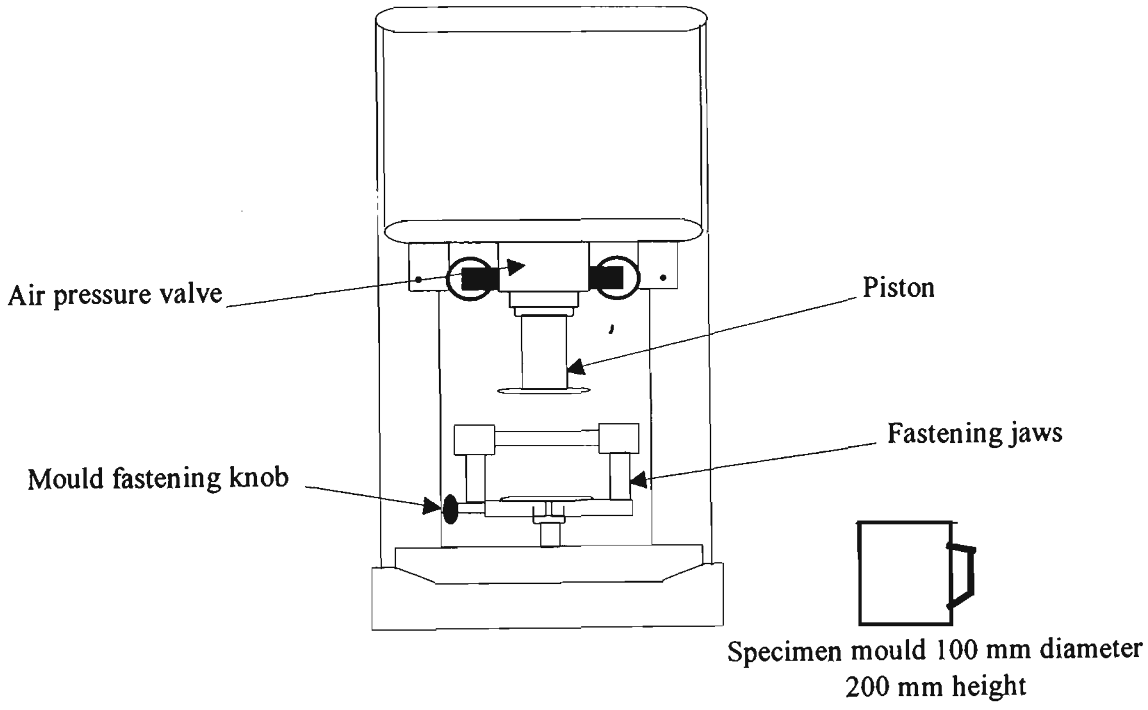

Figure 4.4 ICT apparatus and specimen mould.

RESILIENT MODULUS TESTING

A description of the resilient modulus test is given below:

1. The RAP specimens were taken from the respective curing environment and equilibrated to 25°C before testing. Room temperature specimens were placed in the controlled temperature cabinet for a maximum of 4

hours, whereas specimens cured at elevated temperatures were allowed to cool for 2 hours before being placed in the cabinet for a maximum of 4 hours to bring the specimens to the specified test temperature of 25 ±0.5°C.

2. Once at the desired temperature, the specimen was placed on the loading platen and positioned so that the longitudinal axis of the specimen was parallel to the loading strips. It was important that:
    (a) The specimen sat properly between the loading strips to avoid any significant movements that would produce false readings of strain.
    (b) There be no projections or depressions which would prevent a proper seating of the loading strips on the specimen.

The position of the specimen was then marked with a felt pen to ensure that the same position and alignment could be obtained in future testing.

3. The electronic measuring system was then adjusted and balanced as necessary and the horizontal transducers were mounted in the yoke. At this point adjustments were made in order to bring the LVDTs within the correct working range.

4. Before the commencement of the testing, the relevant information about the specimen was entered in the PC, which included sample identification number, date of testing, specimen length, specimen diameter and applied load.

The diameter and length of specimens were determined using callipers. Four measurements were taken for the length, and the average value expressed to the nearest 0.1mm was entered as the true length of the specimen. The same was done for the diameter, except that only two measurements were taken and the average reported as the true diameter.

The following parameters were left as constants throughout the testing:

Temperature : 25°C
Rise Time: 50ms
Pre-conditioning : 5 Pulses
Load cycle time : 3 seconds
Permissible strain range: 10-100με
Poisson's ratio : 0.4 (assumed value)

5. After all parameters were entered, the specimen was pre-conditioned in order to reduce experimental errors due to poor seating of the specimen in the measuring device. The pre-conditioning consisted of five consecutive identical load pulses with a duration of 2 seconds. If horizontal deformation was greater than 10με and less than 100με, testing was continued. If the strain reading was outside the ranges, the applied force was changed - to a smaller value if strains were greater than 100με, and to a larger value if the obtained strains were smaller than 10με.

6. Once the pre-conditioning period was finished and the results were acceptable, the resilient modulus test was commenced by applying five load pulses of the same magnitude as the conditioning pulses. Originally 500N was applied to all specimens, which was later changed to 1200N when specimens became stiffer and the horizontal strains were outside the permissible limits. (The draft standard resilient modulus test requires a standard load of 1200N to be applied).

7. Resilient modulus was calculated from:

$$E = \frac{P(\nu + 0.27)}{Ht}$$

where:

E = Total resilient modulus, MPa

P = Repeated load, N

t = Thickness of test specimen, mm

ν = Poisson's ratio

H = Total recoverable horizontal deformation, mm

8. After the testing was completed, the results were printed out and the specimen removed from the testing cabinet. Another specimen was placed, and the same steps followed until all specimens were tested. Once all specimens were tested for modulus, they were returned to their respective curing environments.

VISCOSITY OF BITUMEN IN RAP

The determination of the apparent viscosity by mean of the 'Shell' sliding plate micro-viscometer was performed as follows:

The bitumen recovery began with the mixing of a 50g RAP sample with 10ml of toluene. The solution obtained was decanted into a tube and then centrifuged to separate the finer particles from the solution. The separated solution was transferred to a specimen tube and syringed evenly on to two clean micro-viscometer glass plates of known mass. The plates were placed on an evaporating assembly which is positioned on a hot plate at a temperature of

110°C ± 2°C. The evaporation assembly is connected to a carbon dioxide source to stop the binder from oxidising. Figure 4.11 depicts the evaporating assembly.

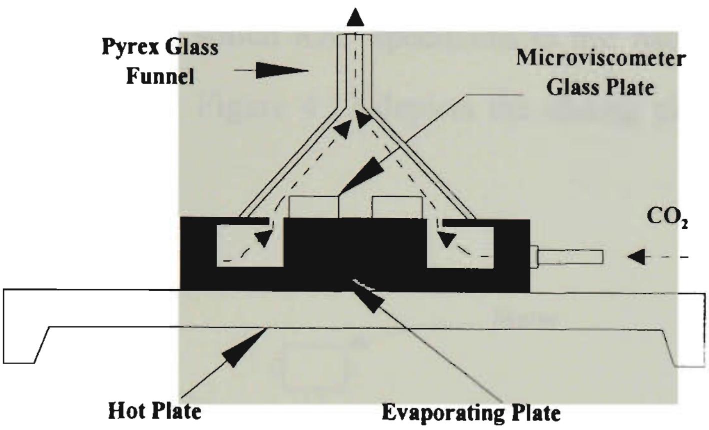

Figure 4.11 Cross-section of evaporation assembly.

The plates were removed from the evaporation assembly after 20 minutes and carefully placed on top of the other. They were pressed together in other to form an even film thickness of 50µm to 100µm. The thickness and uniformity was checked by viewing the filament of a tungsten lamp through the bitumen film. Then the edges and outside of the plates were cleaned, and the plates weighed to more accurately check the thickness. This was done using the following equation:

$$t = \frac{m}{A\rho} \qquad (4.10)$$

where:

t = bitumen film thickness (m)

m = mass of sample between plates (kg)

A = plate area ($6 \times 10^{-4}\, m^2$)

ρ = density of sample ($1000 kg/m^3$)[1]

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[1] This density is used for practical purposes for a sample at 45°C.

If the thickness was between 50μm and 100μm, the test was continued, otherwise it was repeated. The test was performed at 45°C. Because of the expense involved in performing the test, the number of tests was restricted to ten, and the decision of which RAP specimens to test had to be made after all testing was completed. Figure 4.12 depicts the sliding plate micro-viscometer apparatus.

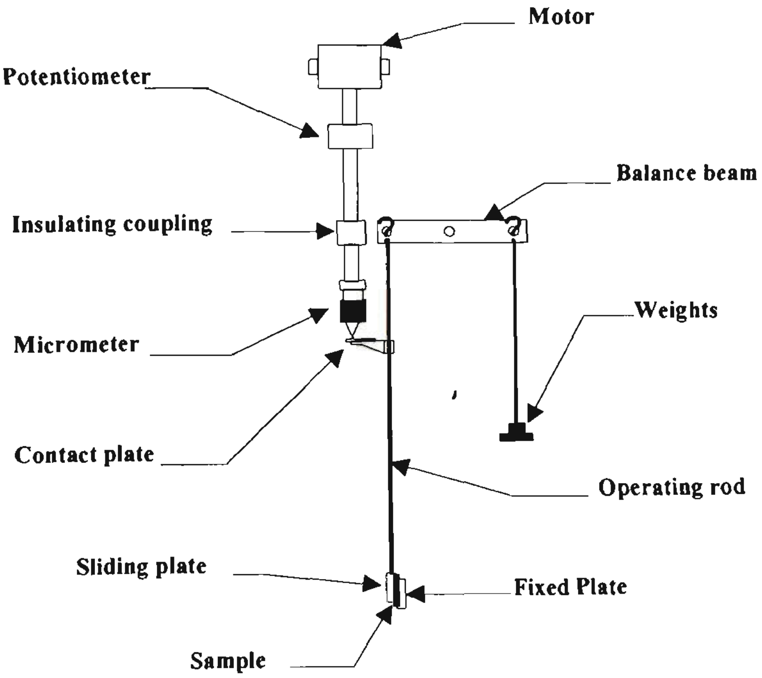


Figure 4.12 Sliding plate micro-viscometer apparatus.

APPENDIX D

MOISTURE CONTENT OF RAP AND GRADINGS FOR RAP AND CLEAN AGGREGATE

- **Moisture Content**
- **RAP Grading**
- **Clean Aggregate Grading**
- **Grading Adjustments**

MOISTURE CONTENT

SPECIMEN NUMBER	WET MASS (g)	DRY MASS (g)	MASS OF WATER (g)	MOISTURE CONTENT (%)
1	1593.3	1543.9	49.4	3.2
2	1658.1	1606.6	51.5	3.2
3	1582.4	1533.8	48.7	3.2
4	1616.9	1568.4	48.5	3.1
5	1626.3	1575.1	51.2	3.3

Determination of rap moisture content according with AS 1289.B1.1 (1977).

GRADINGS

RAP GRADING

SIEVE SIZE (mm)	CUMULATIVE PERCENTAGE PASSING				
	SPECIMEN 1	SPECIMEN 2	SPECIMEN 3	SPECIMEN 4	SPECIMEN 5
26.5	100.0	100.0	100.0	100.0	100.0
19.0	98.8	100.0	99.3	99.4	100
13.2	88.4	89.9	89.4	90.4	89.4
9.50	77.9	75.9	78.6	77.7	77.9
6.70	63.3	60.6	63.9	63.5	64.0
4.75	49.4	48.2	51.3	51.2	49.7
2.36	30.7	29.3	131.6	33.5	32.6
1.18	17.5	17.8	18.4	20.6	20.1
0.06	8.9	10.0	9.6	11.7	11.5
0.03	3.2	4.3	3.9	5.2	5.1
0.015	0.9	1.3	1.1	1.7	1.7
0.075	0.3	0.3	0.3	0.5	0.5

Grading of five RAP specimens in accordance with AS 1141.11 (1980)

CLEAN AGGREGATE GRADING

SIEVE SIZE (mm)	CUMULATIVE PERCENTAGE PASSING				
	SPECIMEN 1	SPECIMEN 2	SPECIMEN 3	SPECIMEN 4	SPECIMEN 5
26.5	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	99.3	99.4	100.0
13.2	93.9	94.0	95.0	94.7	92.8
9.50	87.3	86.6	88.2	87.6	85.6
6.70	78.3	76.7	79.1	79.1	76.2
4.75	67.9	66.4	168.5	68.9	66.4
2.36	52.3	51.8	52.7	53.8	50.4
1.18	40.9	40.6	41.0	42.4	39.5
0.06	32.0	32.1	32.3	33.6	30.8
0.03	23.3	22.5	22.5	23.8	22.4
0.015	13.7	13.0	13.0	13.8	13.0
0.075	8.8	8.8	8.9	9.2	8.6

Grading of five specimens after bitumen extraction in accordance with AS 1141.11 (1980)

GRADING ADJUSTMENTS

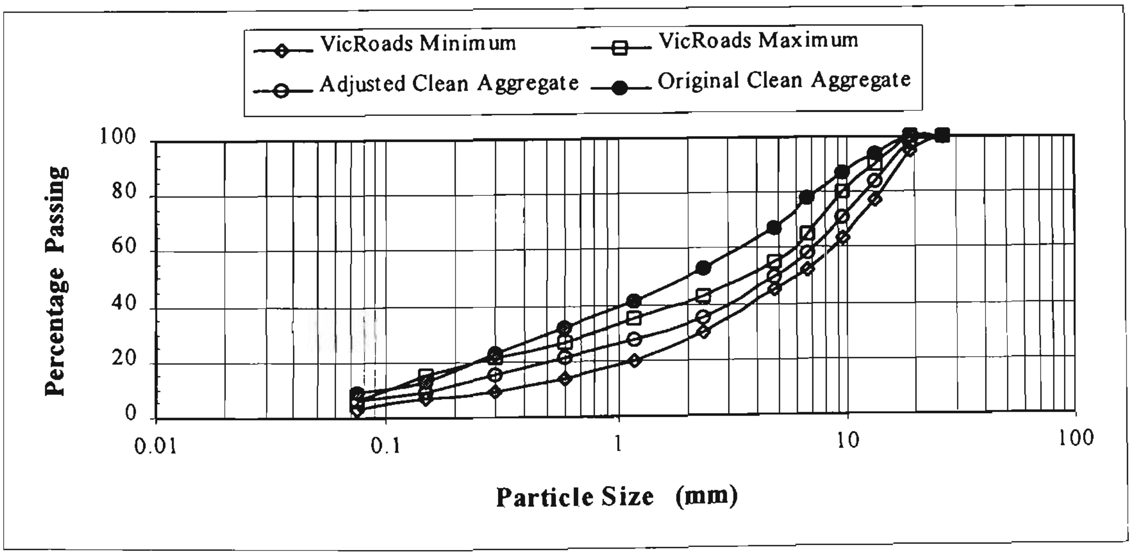
The grading adjustment of RAP can be done by wasting a portion of the aggregate of a particular size or sizes that are in excess and later added with new crushed stone or RAP aggregate of the wasted particle size. This method of wasting and adding is more favourable as the sample mass is kept constant (what is wasted is later added) eliminating in this way the overloading of sieves.

The method used to adjust the aggregate grading is based on trial and error calculations and is described in the Asphalt Handbook (1989). The following Table shows the average adjusted grading for the clean aggregate. These results are only an indication of how the aggregate can be adjusted in other to produce a well-graded material.

SIEVE SIZE mm	VIC ROADS SPECIFICATIONS	ORIGINAL AVERAGE PERCENTAGE PASSING	ADJUSTED AVERAGE PERCENTAGE PASSING
26.5	100	100.0	100.0
19.0	95-100	99.7	97.5
13.2	77-90	94.1	83.6
9.5	63-80	87.1	71.3
6.70	52-65	77.8	57.9
4.75	45-55	67.4	50.0
2.36	30-43	52.3	35.3
1.18	20-35	40.9	27.6
0.600	14-27	32.2	21.7
0.300	9-21	22.8	15.5
0.150	7-15	13.2	9.0
0.075	3-6	8.92	6.0

Cumulative percentage passing for, Vic Roads requirement limits for Asphalt and original and adjusted clean aggregate.

The Figure below shows the average adjusted clean aggregate grading obtained together with the Vic Roads specification limits and the average clean aggregate grading before adjustment. It should be emphasised that this adjustment was not made on the material tested in this project.



Adjusted clean aggregate grading, Vic Roads specification limits and original clean aggregate grading.

ADJUSTING BY WASTING

Specimen No.: 1 Sample mass: 1467.77 g

TRIALS	P_2
1	50
2	47
3	46

Above waste: $R_b = \frac{R_2 R_a}{R_1}$ Below waste: $P_b = \frac{P_2 P_a}{P_1}$

P_b, R_b = **adjusted** passing or retained of given size **after wasting.**
P_a, R_a = percent passing or retained of given size **before wasting.**
P_1, R_1 = percentage passing or retained of **waste** size **before wasting.**
P_2, R_2 = percentage passing or retained of **waste** size **after wasting.**

P_2 = 46 P_1 = 67.9 P_2/P_1 = 0.677
R_2 = 54 R_1 = 32.1 R_2/R_1 = 1.682

Sieve size mm	VicRoads Spec. %	Sample % Passing	Sample % Retained	Pb Adjusted % Passing	Rb Adjusted % Retained	Total Adjusted % Passing	VicRoads Spec. %
26.5	100	100.0	0.0		0.0	100.0	100
19.0	95-100	100.0	0.0		0.0	100.0	95-100
13.2	77-90	93.9	6.1		10.3	89.7	77-90
9.5	63-80	87.3	12.7		21.4	78.6	63-80
6.70	52-65	78.3	21.7		36.5	63.5	52-65
4.75	**45-55**	**67.9**	**32.1**	**46.0**	**54.0**	**46.0**	**45-55**
2.36	30-43	52.3	47.7	35.4		35.4	30-43
1.18	20-35	40.9	59.1	27.7		27.7	20-35
0.600	14-27	32.0	68.0	21.7		21.7	14-27
0.300	9-21	23.3	76.7	15.8		15.8	9-21
0.150	7-15	13.7	86.3	9.3		9.3	7-15
0.075	3-6	8.8	91.2	6.0		6.0	3-6

Waste, $W = \frac{100(P_1 - P_2)}{(100 - P_2)}$ W = 40.6 %

mass of waste = 595.3 g

FINAL ADJUSTMENT BY ADDING NEW MATERIAL

$$a = \frac{P-B}{A-B} \qquad \therefore b = 1 - a$$

P	Percentage of material passing a given size for combined aggregates A,B (target)
A,B	Percentage of material passing a given sieve for aggregates A,B
a,b	Proportion of aggregates, A, B used in the combination and where the total =1.00

Sieve Size mm	VicRoads specifications	A total adjusted % passing	B Virgin Aggregate % Passing	P Target	a 0.556	b 0.444	Final Adjusted % Passing	Mass of Virgin Aggregrate to add g
26.5	100	100	100		55.6	44.4	100.0	566.3
19.0	95-100	100	95		55.6	42.2	97.8	537.99
13.2	77-90	89.7	77		49.8	34.2	84.1	436.05
9.5	63-80	78.6	63		43.7	28.0	71.7	356.77
6.70	52-65	63.5	52		35.3	23.1	58.4	294.48
4.75	**45-55**	**46.0**	**55**	**50.0**	25.6	24.4	50.0	311.47
2.36	30-43	35.4					35.4	
1.18	20-35	27.7					27.7	
0.600	14-27	21.7					21.7	
0.300	9-21	15.8					15.8	
0.150	7-15	9.3					9.3	
0.075	3-6	6.0					6.0	

Sieve Size mm	Cum. Mass Retained g	Cum. mass Passing g	Final Adjusted % Passing	Min. V'Roads Spec.	Max. V'Roads Spec.
26.5	0.00	1467.77	100.0	100	100
19.0	32.62	1435.15	97.8	95	100
13.2	234.03	1233.74	84.1	77	90
9.5	415.87	1051.90	71.7	63	80
6.70	610.76	857.01	58.4	52	65
4.75	**733.89**	**733.89**	**50.0**	**45**	**55**
2.36	948.18	519.59	35.4	30	43
1.18	1061.20	406.57	27.7	20	35
0.600	1379.54	88.23	21.7	14	27
0.300	1235.86	231.91	15.8	9	21
0.150	1331.27	136.50	9.3	7	15
0.075	1379.70	88.07	6.0	3	6
	1467.77	0.00	0.0		

ADJUSTING BY WASTING

Specimen No.: 2 Sample mass 1535.13 g

TRIALS	P_2
1	46
2	45.5
3	

Above waste: $R_b = \frac{R_2 R_a}{R_1}$ Below waste: $P_b = \frac{P_2 P_a}{P_1}$

P_b, R_b = **adjusted** passing or retained of given size **after wasting.**
P_a, R_a = percent passing or retained of given size **before wasting.**
P_1, R_1 = percentage passing or retained of **waste size before wasting.**
P_2, R_2 = percentage passing or retained of **waste size after wasting.**

P_2 = 45.5 P_1 = 66.4 P_2/P_1 = 0.685
R_2 = 54.5 R_1 = 33.6 R_2/R_1 = 1.622

Sieve size mm	VicRoads Specif. %	Sample % Passing	Sample % Retained	Pb Adjusted % Passing	Rb Adjusted % Retained	Total Adjusted % Passing	VicRoads Specif. %
26.5	100	100.0	0.0		0.0	100.0	100
19.0	95-100	100.0	0.0		0.0	100.0	95-100
13.2	77-90	94.0	6.0		9.7	90.3	77-90
9.5	63-80	86.6	13.4		21.7	78.3	63-80
6.70	52-65	76.7	23.3		37.8	62.2	52-65
4.75	**45-55**	**66.4**	**33.6**	**45.5**	**54.5**	**45.5**	**45-55**
2.36	30-43	51.8	48.2	35.5		35.5	30-43
1.18	20-35	40.6	59.4	27.8		27.8	20-35
0.600	14-27	32.1	67.9	22.0		22.0	14-27
0.300	9-21	22.5	77.5	15.4		15.4	9-21
0.150	7-15	13.0	87.0	8.9		8.9	7-15
0.075	3-6	8.8	91.2	6.0		6.0	3-6

Waste, $W = \frac{100(P_1 - P_2)}{(100 - P_2)}$ W = 38.3 %

mass of waste = 588.7 g

FINAL ADJUSTMENT BY ADDING NEW MATERIAL

$$a = \frac{P - B}{A - B} \qquad \therefore b = 1 - a$$

P	Percentage of material passing a given size for combined aggregates A,B (target)
A,B	Percentage of material passing a given sieve for aggregates A,B
a,b	Proportion of aggregates, A, B used in the combination and where the total =1.00

					0.53	0.47		
Sieve Size mm	VicRoads Specif.	A total adjusted % passing	B Virgin Aggregate % Passing	P Target	a	b	Final Adjusted % Passing	Mass of Virgin Aggegrate to add g
26.5	100	100.0	100		52.6	47.4	100.0	566.3
19.0	95-100	100.0	95		52.6	45.0	97.6	537.99
13.2	77-90	90.3	77		47.5	36.5	84.0	436.05
9.5	63-80	78.3	63		41.2	29.8	71.0	356.77
6.70	52-65	62.2	52		32.7	24.6	57.4	294.48
4.75	**45-55**	**45.5**	**55**	**50.0**	23.9	26.1	50.0	311.47
2.36	30-43	35.5					35.5	
1.18	20-35	27.8					27.8	
0.600	14-27	22.0					22.0	
0.300	9-21	15.4					15.4	
0.150	7-15	8.9					8.9	
0.075	3-6	6.0					6.0	

Sieve Size mm	Cum. Mass Retained g	Cum. mass Passing g	Final Adjusted % Passing	Min. V'Roads Specif.	Max. V'Roads Specif.
26.5	0.00	1535.13	100.0	100	100
19.0	36.36	1498.77	97.6	95	100
13.2	245.88	1289.25	84.0	77	90
9.5	444.66	1090.47	71.0	63	80
6.70	654.39	880.74	57.4	52	65
4.75	**767.57**	**767.57**	**50.0**	**45**	**55**
2.36	990.23	544.90	35.5	30	43
1.18	1108.04	427.09	27.8	20	35
0.600	1441.19	93.94	22.0	14	27
0.300	1298.44	236.69	15.4	9	21
0.150	1398.38	136.75	8.9	7	15
0.075	1442.56	92.57	6.0	3	6
	1535.13	0.00	0.0		

ADJUSTING BY WASTING

Specimen No.: 3 Sample mass: 1461.4 g

TRIALS	P_2
1	46
2	
3	

Above waste: $R_b = \dfrac{R_2 R_a}{R_1}$ Below waste: $P_b = \dfrac{P_2 P_a}{P_1}$

P_b, R_b = **adjusted** passing or retained of given size **after wasting.**
P_a, R_a = percent passing or retained of given size **before wasting.**
P_1, R_1 = percentage passing or retained of **waste** size **before wasting.**
P_2, R_2 = percentage passing or retained of **waste** size **after wasting.**

P_2 = 46 P_1 = 68.5 P_2/P_1 = 0.672
R_2 = 54 R_1 = 31.5 R_2/R_1 = 1.714

Sieve size mm	VicRoads Spec. %	Sample % Passing	Sample % Retained	Pb Adjusted % Passing	Rb Adjusted % Retained	Total Adjusted % Passing	VicRoads Spec. %
26.5	100	100.0	0.0		0.0	100.0	100
19.0	95-100	99.3	0.7		1.2	98.8	95-100
13.2	77-90	95.0	5.0		8.6	91.4	77-90
9.5	63-80	88.2	11.8		20.2	79.8	63-80
6.70	52-65	79.1	20.9		35.8	64.2	52-65
4.75	**45-55**	**68.5**	**31.5**	**46.0**	**54.0**	**46.0**	**45-55**
2.36	30-43	52.7	47.3	35.4		35.4	30-43
1.18	20-35	41.0	59.0	27.5		27.5	20-35
0.600	14-27	32.3	67.7	21.7		21.7	14-27
0.300	9-21	22.5	77.5	15.1		15.1	9-21
0.150	7-15	13.0	87.0	8.7		8.7	7-15
0.075	3-6	8.9	91.1	6.0		6.0	3-6

Waste, $W = \dfrac{100(P_1 - P_2)}{(100 - P_2)}$ W = 41.7 %

mass of waste = 608.9 g

FINAL ADJUSTMENT BY ADDING NEW MATERIAL

$$a = \frac{P - B}{A - B} \qquad \therefore b = 1 - a$$

P	Percentage of material passing a given size for combined aggregates A,B (target)
A,B	Percentage of material passing a given sieve for aggregates A,B
a,b	Proportion of aggregates, A, B used in the combination and where the total =1.00

					0.556	0.444		
Sieve Size mm	VicRoads specifications	A total adjusted % passing	B Virgin Aggregate % Passing	P Target	a	b	Final Adjusted % Passing	Mass of Virgin Aggregate to add g
26.5	100	100.0	100		55.6	44.4	100.0	566.3
19.0	95-100	98.8	95		54.9	42.2	97.1	537.99
13.2	77-90	91.4	77		50.8	34.2	85.0	436.05
9.5	63-80	79.8	63		44.3	28.0	72.3	356.77
6.70	52-65	64.2	52		35.7	23.1	58.8	294.48
4.75	**45-55**	**46.0**	**55**	**50.0**	25.6	24.4	50.0	311.47
2.36	30-43	35.4					35.4	
1.18	20-35	27.5					27.5	
0.600	14-27	21.7					21.7	
0.300	9-21	15.1					15.1	
0.150	7-15	8.7					8.7	
0.075	3-6	6.0					6.0	

Sieve Size mm	Cum. Mass Retained g	Cum. mass Passing g	Final Adjusted % Passing	Min. V'Roads Spec.	Max. V'Roads Spec.
26.5	0.00	1461.4	100.0	100	100
19.0	42.22	1419.18	97.1	95	100
13.2	218.98	1242.42	85.0	77	90
9.5	404.55	1056.85	72.3	63	80
6.70	602.65	858.75	58.8	52	65
4.75	**730.70**	**730.70**	**50.0**	**45**	**55**
2.36	944.21	517.19	35.4	30	43
1.18	1059.03	402.37	27.5	20	35
0.600	1374.12	87.28	21.7	14	27
0.300	1240.59	220.81	15.1	9	21
0.150	1333.82	127.58	8.7	7	15
0.075	1374.06	87.34	6.0	3	6
	1461.40	0.00	0.0		

ADJUSTING BY WASTING

Specimen No.: 4 Sample mass: 1495.56 g

TRIALS	P_2
1	46
2	45.7
3	45.5
4	45

Above waste: $R_b = \frac{R_2 R_a}{R_1}$ Below waste: $P_b = \frac{P_2 P_a}{P_1}$

P_b, R_b = **adjusted** passing or retained of given size **after wasting.**
P_a, R_a = percent passing or retained of given size **before wasting.**
P_1, R_1 = percentage passing or retained of **waste** size **before wasting.**
P_2, R_2 = percentage passing or retained of **waste** size **after wasting.**

P_2 = 45 P_1 = 68.9 P_2/P_1 = 0.653
R_2 = 55 R_1 = 31.1 R_2/R_1 = 1.768

Sieve size mm	VicRoads Spec. %	Sample % Passing	Sample % Retained	Pb Adjusted % Passing	Rb Adjusted % Retained	Total Adjusted % Passing	VicRoads Spec. %
26.5	100	100.0	0.0		0.0	100.0	100
19.0	95-100	99.4	0.6		1.1	98.9	95-100
13.2	77-90	94.7	5.3		9.4	90.6	77-90
9.5	63-80	87.6	12.4		21.9	78.1	63-80
6.70	52-65	79.1	20.9		37.0	63.0	52-65
4.75	**45-55**	**68.9**	**31.1**	**45.0**	**55.0**	**45.0**	**45-55**
2.36	30-43	53.8	46.2	35.1		35.1	30-43
1.18	20-35	42.4	57.6	27.7		27.7	20-35
0.600	14-27	33.6	66.4	21.9		21.9	14-27
0.300	9-21	23.8	76.2	15.5		15.5	9-21
0.150	7-15	13.8	86.2	9.0		9.0	7-15
0.075	3-6	9.2	90.8	6.0		6.0	3-6

Waste, $W = \frac{100(P_1 - P_2)}{(100 - P_2)}$ W = 43.5 %

mass of waste = 649.9 g

FINAL ADJUSTMENT BY ADDING NEW MATERIAL

$$a = \frac{P-B}{A-B} \qquad \therefore b = 1 - a$$

P	Percentage of material passing a given size for combined aggregates A,B (target)
A,B	Percentage of material passing a given sieve for aggregates A,B
a,b	Proportion of aggregates, A, B used in the combination and where the total =1.00

					0.500	0.500		
Sieve Size mm	VicRoads specifications	A total adjusted % passing	B Virgin Aggregate % Passing	P Target	a	b	Final Adjusted % Passing	Mass of Virgin Aggregate to add g
26.5	100	100.0	100		50.0	50.0	100.0	566.3
19.0	95-100	98.9	95		49.5	47.5	97.0	537.99
13.2	77-90	90.6	77		45.3	38.5	83.8	436.05
9.5	63-80	78.1	63		39.0	31.5	70.5	356.77
6.70	52-65	63,0	52		31.5	26.0	57.5	294.48
4.75	**45-55**	45.0	**55**	**50.0**	22.5	27.5	50.0	311.47
2.36	30-43	35.1					35.1	
1.18	20-35	27.7					27.7	
0.600	14-27	21.9					21.9	
0.300	9-21	15.5					15.5	
0.150	7-15	9.0					9.0	
0.075	3-6	6.0					6.0	

Sieve Size mm	Cum. Mass Retained g	Cum. mass Passing g	Final Adjusted % Passing	Min. V'Roads Spec.	Max. V'Roads Spec.
26.5	0.00	1495.56	100.0	100	100
19.0	45.32	1450.24	97.0	95	100
13.2	242.08	1253.48	83.8	77	90
9.5	440.66	1054.90	70.5	63	80
6.70	635.32	860.24	57.5	52	65
4.75	**747.78**	**747.78**	**50.0**	**45**	**55**
2.36	970.05	525.51	35.1	30	43
1.18	1081.40	414.16	27.7	20	35
0.600	1404.67	90.89	21.9	14	27
0.300	1263.09	232.47	15.5	9	21
0.150	1360.76	134.80	9.0	7	15
0.075	1405.70	89.86	6.0	3	6
	1495.56	0.00	0.0		

ADJUSTING BY WASTING

Specimen No.: 5 Sample mass: 1499.08 g

TRIALS	P_2
1	46
2	
3	

Above waste: $R_b = \frac{R_2 R_a}{R_1}$ Below waste: $P_b = \frac{P_2 P_a}{P_1}$

P_b, R_b = **adjusted** passing or retained of given size **after wasting.**
P_a, R_a = percent passing or retained of given size **before wasting.**
P_1, R_1 = percentage passing or retained of **waste** size **before wasting.**
P_2, R_2 = percentage passing or retained of **waste** size **after wasting.**

P_2 = 46 P_1 = 66.4 P_2/P_1 = 0.693
R_2 = 54 R_1 = 33.6 R_2/R_1 = 1.607

Sieve size mm	VicRoads Spec. %	Sample % Passing	Sample % Retained	Pb Adjusted % Passing	Rb Adjusted % Retained	Total Adjusted % Passing	VicRoads Spec. %
26.5	100	100.0	0.0		0.0	100.0	100
19.0	95-100	100.0	0.0		0.0	100.0	95-100.
13.2	77-90	92.8	7.2		11.6	88.4	77-90
9.5	63-80	85.6	14.4		23.1	76.9	63-80
6.70	52-65	76.2	23.8		38.3	61.8	52-65
4.75	**45-55**	**66.4**	**33.6**	**46.0**	**54.0**	**46.0**	**45-55**
2.36	30-43	50.4	49.6	34.9		34.9	30-43
1.18	20-35	39.5	60.5	27.4		27.4	20-35
0.600	14-27	30.8	69.2	21.3		21.3	14-27
0.300	9-21	22.4	77.6	15.5		15.5	9-21
0.150	7-15	13.0	87.0	9.0		9.0	7-15
0.075	3-6	8.6	91.4	6.0		6.0	3-6

Waste, $W = \frac{100(P_1 - P_2)}{(100 - P_2)}$ W = 37.8 %

mass of waste = 566.3 g

FINAL ADJUSTMENT BY ADDING NEW MATERIAL

$$a=\frac{P-B}{A-B} \qquad \therefore b=1-a$$

P	Percentage of material passing a given size for combined aggregates A,B (target)
A,B	Percentage of material passing a given sieve for aggregates A,B
a,b	Proportion of aggregates, A, B used in the combination and where the total =1.00

					0.556	0.444		
Sieve Size mm	VicRoads specifications	A total adjusted % passing	B Virgin Aggregate % Passing	P Target	a	b	Final Adjusted % Passing	Mass of Virgin Aggregate to add g
26.5	100	100.0	100		55.6	44.4	100.0	566.3
19.0	95-100	100.0	95		55.6	42.2	97.8	537.99
13.2	77-90	88.4	77		49.1	34.2	83.3	436.05
9.5	63-80	76.9	63		42.7	28.0	70.7	356.77
6.70	52-65	61.8	52		34.3	23.1	57.4	294.48
4.75	**45-55**	46.0	**55**	**50.0**	25.6	24.4	50.0	311.47
2.36	30-43	34.9					34.9	
1.18	20-35	27.4					27.4	
0.600	14-27	21.3					21.3	
0.300	9-21	15.5					15.5	
0.150	7-15	9.0					9.0	
0.075	3-6	6.0					6.0	

Sieve Size mm	Cum. Mass Retained g	Cum. mass Passing g	Final Adjusted % Passing	Min. V'Roads Spec.	Max. V'Roads Spec.
26.5	0.00	1499.08	100.0	100	100
19.0	33.31	1465.77	97.8	95	100
13.2	249.61	1249.47	83.3	77	90
9.5	439.25	1059.83	70.7	63	80
6.70	638.36	860.72	57.4	52	65
4.75	**749.54**	**749.54**	**50.0**	**45**	**55**
2.36	975.67	523.41	34.9	30	43
1.18	1088.86	410.22	27.4	20	35
0.600	1411.55	87.53	21.3	14	27
0.300	1266.45	232.63	15.5	9	21
0.150	1364.07	135.01	9.0	7	15
0.075	1409.77	89.31	6.0	3	6
	1499.08	0.00	0.0		

APPENDIX E

BITUMEN CONTENT AND REJUVENATOR CONTENT

- **Bitumen Content**
- **Rejuvenator Content**
  1. **Percentage Bitumen Demand of Clean Aggregate**
  2. **Percentage of New Bitumen in Mix**
  3. **Total Percent of Rejuvenator to Add to RAP**

BITUMEN CONTENT

The bitumen content was calculated using the following equation:

$$\text{Bitumen Content} = \frac{m_b}{m_s} \times 100$$

where:

m_b = bitumen mass, g

m_s = sample dry mass, g

$$m_b = m_s + m_8$$

where:

m_8 = total dry aggregate, g

$$m_8 = m_6 + m_7$$

where:

m_6 = dry washed aggregate, g

m_7 = total fines, g

$$m_7 = m_5 - m_4 - m_1$$

where:

m_5 = mass of filter pad + fines + filter aid, g

m_4 = filter pad mass, g

m_1 = filter aid mass, g

Specimen No.	Specimen Mass m_s g	Filter Aid + Filter Pad, $m_1 + m_4$ g	Filter Pad + Fines + Filter Aid m_5 g	Dry Washed Aggregate m_6 g	Fines m_7 g	Total Dry Aggregate m_8 g	Bitumen m_b g	Bitumen Content %
1	1543.87	70.0	172.69	1366.78	102.69	1469.47	74.40	4.8
2	1606.55	70.0	168.29	1435.90	98.29	1534.19	1534.19	4.5
3	1533.82	70.0	173.02	1357.54	103.02	1460.56	73.26	4.8
4	1568.38	70.0	185.27	1380.09	115.27	1495.36	73.02	4.7
5	1575.05	70.0	178.16	1398.43	108.16	1506.59	68.49	4.3

Table shows the results obtained from five specimens. The bitumen content obtained was used in the calculation of the rejuvenator content.

REJUVENATOR CONTENT

The rejuvenator content was calculated using the Asphalt Institute formula. The following is a calculated example, using the results for specimen one presented in Appendix A for Clean Aggregate Grading and Appendix B Bitumen Content.

1. PERCENTAGE BITUMEN DEMAND OF CLEAN AGGREGATE.

Using equation 4.1 the following was obtained:

$$\mathbf{P_c = 0.035a + 0.045b + Kc + F}$$

where:

$a = 47.7\%$ $\quad K = 0.18$

$b = 43.5\%$ $\quad F = 0.85$

$c = 8.8\%$

$$\therefore \quad P_c = [(0.035 \times 47.7) + (0.045 \times 43.5) + (0.18 \times 8.8) + 0.85]$$

$$\mathbf{P_c = 6.1\%}$$

2. PERCENTAGE OF NEW BITUMEN IN MIX.

Using equation 4.2 the following was obtained:

$$P_r = P_c - (P_a \times P_p)$$

where:

$P_c = 6.1\%$ $\quad P_p = 1.0$

$P_a = 4.8\%$

$$\therefore\ P_r = 6.1 - (4.8 \times 1.0)$$

$$\mathbf{P_r = 1.3\%}$$

3. TOTAL PERCENT OF REJUVENATOR TO ADD TO RAP.

Using equation 4.4 the following was obtained:

$$P_b = \frac{P_r}{65} \times 100$$

$$\therefore\ P_b = \frac{1.3}{65} \times 100$$

$$\mathbf{P_b = 2.0\%}$$

The results obtained for all specimens are presented in the following table:

Specimen Number	Bitumen Content %	Bitumen Demand P_c %	Rejuvenator Content P_r %	Amount of Rejuvenator to Add P_b %
1	4.8	6.1	1.3	2.0
2	4.5	6.1	1.6	2.5
3	4.8	6.1	1.3	2.0
4	4.7	6.1	1.4	2.2
5	4.3	6.0	1.7	2.6

APPENDIX F

VOID-FREE BULK DENSITY

- **Void-Free Bulk Density**
- **Percentage Voids**

VOID FREE BULK DENSITY

The void-free bulk density was calculated using the Vic Roads test method RC 202.01. The results obtained were as follows:

$$\mathrm{VFBD} = \frac{(m_1 - m_2)}{(m_2 - m_1) - (m_3 - m_4)} \times \rho_w$$

where:

m_1 = mass of pycnometer and lid, (g)

m_2 = mass of pycnometer, lid and sample, (g)

m_3 = mass of pycnometer, sample, water at 25°C, lid and no air bubbles, (g)

m_4 = calibrated mass of pycnometer full of water at 25°C and lid, (g)

ρ_w = density of water at 25°C, (0.997044g/cm^3).

Specimen Number	m_1 (g)	m_2 (g)	m_3 (g)	m_4 (g)	VFBD (g/cm^3)	AVERAGE VFBD (g/cm^3)
1	1321.8	2152.0	4162.1	3673.9	2.427	2.438
2	1296.8	2062.9	4144.8	3691.5	2.449	

PERCENTAGE VOIDS

$$\text{Percentage voids} = \frac{\mathrm{VFBD} - \rho_B}{\mathrm{VFBD}} \times 100$$

$$\therefore \text{Percentage voids} = 10.0\%$$

where:

ρ_B = 2.197g/cm^3

VFBD = 2.438g/cm^3.

PERCENTAGE VOIDS FOR SPECIMENS IN PROCEDURE ONE, GROUP 1

ELAPSED TIME (Days)	SPECIMEN NUMBER	BULK DENSITY (kg/m^3)	PERCENTAGE VOIDS	VOIDS MEAN	VOIDS SD	VOIDS C.V.%
2	1	2040.8	16.3	-	-	-
5	2	2020.6	17.1	-	-	-
13	3	2007.1	17.7	-	-	-
28	4	1999.3	18.0	**17.8**	**0.1**	**0.8**
	5	2009.2	17.6			
	6	2004.2	17.8			
	7	2002.4	17.9			
	8	2006.8	17.7			
57	3	2004.0	17.8	**17.9**	**0.1**	**0.7**
	4	1997.0	18.1			
	5	2007.1	17.7			
	6	2002.1	17.9			
	7	2000.5	17.9			
	8	2003.6	17.8			
117	3	2005.7	17.7	**17.8**	**0.2**	**0.8**
	4	1998.5	18.0			
	5	2008.5	17.6			
	6	2003.6	17.8			
	7	1998.9	18.0			
	8	2004.7	17.8			

PERCENTAGE VOIDS FOR SPECIMENS IN PROCEDURE ONE, GROUP 2

ELAPSED TIME (Days)	SPECIMEN NUMBER	BULK DENSITY (kg/m^3)	PERCENTAGE VOIDS	VOIDS MEAN	VOIDS SD	VOIDS C.V.%
1	1	2029.1	16.8	**17.0**	**0.2**	**1.0**
	2	2023.2	17.0			
	3	2016.4	17.3			
	4	2024.0	17.0			
	5	2020.4	17.1			
4	1	2012.3	17.5	**17.7**	**0.3**	**1.5**
	2	2007.0	17.7			
	3	1997.1	18.1			
8	1	2013.1	17.4	**17.7**	**0.2**	**1.2**
	2	2007.6	17.7			
	3	1997.7	18.1			
	4	2006.0	17.7			
	5	2004.3	17.8			
15	1	2011.7	17.5	**17.8**	**0.2**	**1.2**
	2	2006.4	17.7			
	3	1996.3	18.1			
	4	2004.9	17.8			
	5	2002.0	17.9			
30	1	2013.4	17.4	**17.7**	**0.2**	**1.2**
	2	2008.3	17.6			
	3	1998.2	18.0			
	4	2006.8	17.7			
	5	2003.9	17.8			
57	1	2010.8	17.5	**17.8**	**0.2**	**1.1**
	2	2005.8	17.7			
	3	1995.8	18.1			
	4	2004.1	17.8			
	5	2001.2	17.9			
113	1	2011.1	17.5	**17.8**	**0.2**	**1.1**
	2	2005.8	17.7			
	3	1996.0	18.1			
	4	2004.3	17.8			
	5	2001.6	17.9			

PERCENTAGE VOIDS FOR SPECIMENS IN PROCEDURE ONE, GROUP 3

ELAPSED TIME (Days)	SPECIMEN NUMBER	BULK DENSITY (kg/m^3)	PERCENTAGE VOIDS	VOIDS MEAN	VOIDS SD	VOIDS C.V.%
1	1	2008.7	17.6	**17.6**	**0.2**	**1.3**
	2	2009.8	17.6			
	3	2020.5	17.1			
	4	2007.6	17.7			
	5	2003.9	17.8			
3	1	2002.6	17.9	**17.7**	**0.2**	**1.1**
	2	2003.9	17.8			
	3	2013.1	17.4			
7	1	2001.4	17.9	**18.0**	**0.1**	**0.5**
	4	2000.0	18.0			
	5	1996.4	18.1			
14	1	2000.9	17.9	**17.9**	**0.2**	**1.2**
	2	2002.9	17.8			
	3	2012.1	17.5			
	4	1999.6	18.0			
	5	1995.8	18.1			
28	1	-	-	**17.9**	**0.3**	**1.5**
	2	2002.1	17.9			
	3	2011.0	17.5			
	4	1995.6	18.1			
	5	1995.3	18.2			
57	1	-	-	**17.9**	**0.3**	**1.5**
	2	2002.1	17.9			
	3	2011.0	17.5			
	4	1995.2	18.2			
	5	1995.1	18.2			
118	1	-	-	**17.9**	**0.3**	**1.5**
	2	2003.7	17.8			
	3	2012.7	17.4			
	4	1996.5	18.1			
	5	1996.4	18.1			

PERCENTAGE VOIDS FOR SPECIMENS IN PROCEDURE TWO

ELAPSED TIME (Days)	SPECIMEN NUMBER	BULK DENSITY (kg/m^3)	PERCENTAGE VOIDS	VOIDS MEAN	VOIDS SD	VOIDS C.V.%
1	1	2034.5	16.6	**16.3**	**0.4**	**2.5**
	2	2055.7	15.7			
	3	2037.9	16.4			
	4	2048.7	16.0			
	5	2028.2	16.8			
8	1	2030.7	16.7	**16.5**	**0.4**	**2.5**
	2	2050.7	15.9			
	3	2033.6	16.6			
	4	2045.0	16.1			
	5	2023.2	17.0			
22	1	2029.9	16.7	**16.5**	**0.4**	**2.6**
	2	2051.5	15.9			
	3	2034.1	16.6			
	4	2046.0	16.1			
	5	2022.7	17.0			
50	1	2028.4	16.8	**16.5**	**0.4**	**2.6**
	2	2050.7	15.9			
	3	2033.7	16.6			
	4	2045.4	16.1			
	5	2021.9	17.1			
98	1	2029.7	16.7	**16.4**	**0.4**	**2.6**
	2	2051.9	15.8			
	3	2035.3	16.5			
	4	2046.4	16.1			
	5	2023.1	17.0			
106	1	2028.2	16.8	**16.5**	**0.4**	**2.6**
	2	2050.4	15.9			
	3	2033.6	16.6			
	4	2045.4	16.1			
	5	2021.9	17.1			

PERCENTAGE VOIDS FOR SPECIMENS IN PROCEDURE THREE

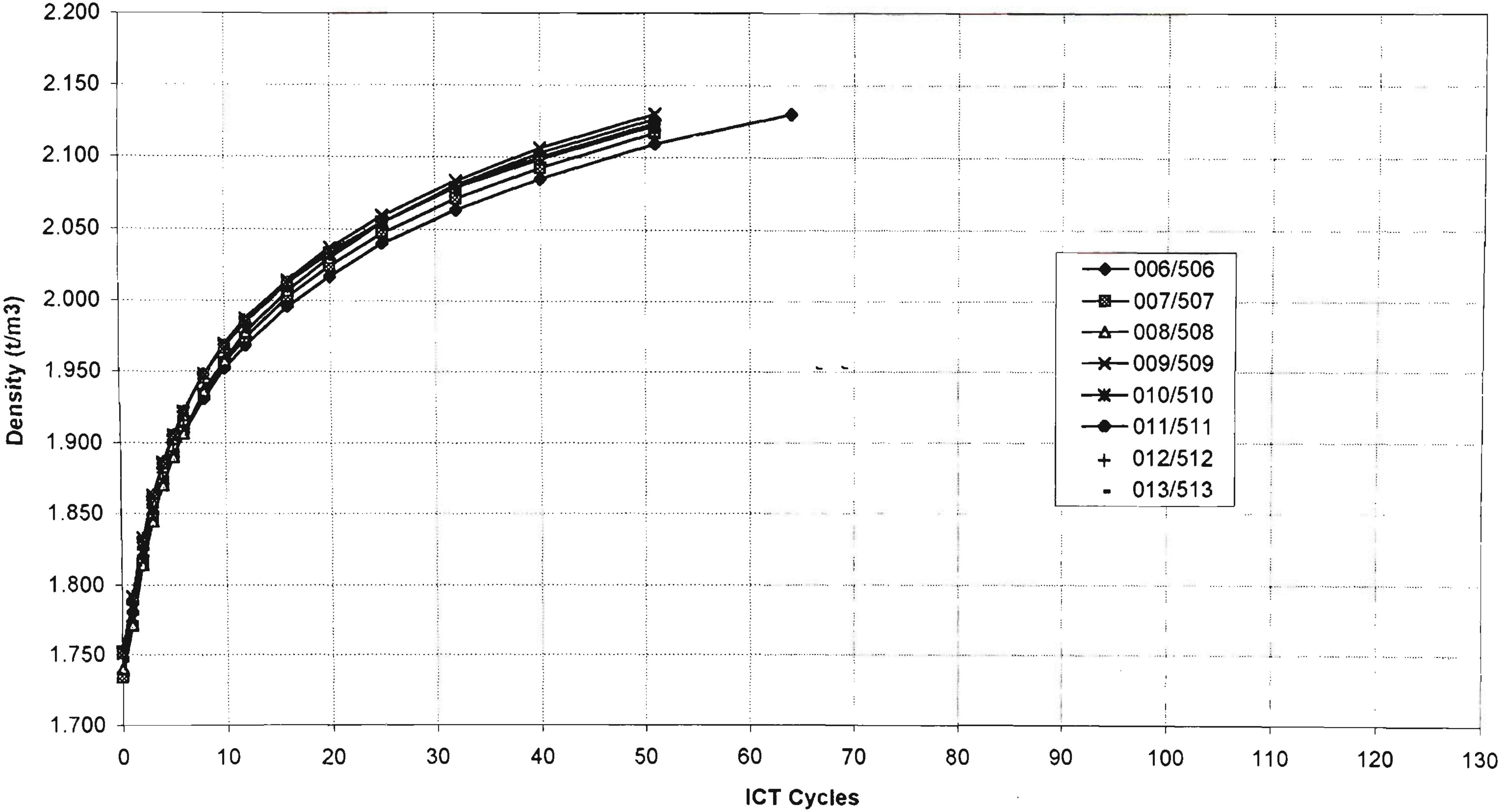
ELAPSED TIME (Days)	SPECIMEN NUMBER	BULK DENSITY (kg/m^3)	PERCENTAGE VOIDS	VOIDS MEAN	VOIDS SD	VOIDS C.V.%
1	1	2031.6	16.7	**16.8**	**0.8**	**4.8**
	2	2048.8	16.0			
	3	2032.2	16.6			
	4	2036.6	16.5			
	5	1990.9	18.3			
7	1	2021.7	17.1	**17.3**	**0.9**	**5.0**
	2	2038.1	16.4			
	3	2023.0	17.0			
	4	2024.0	17.0			
	5	1976.4	18.9			
22	1	2021.1	17.1	**17.3**	**0.9**	**5.0**
	2	2037.2	16.4			
	3	2022.1	17.1			
	4	2023.3	17.0			
	5	1975.4	19.0			
50	1	2020.7	17.1	**17.4**	**0.8**	**4.9**
	2	2036.8	16.5			
	3	2021.1	17.1			
	4	2020.0	17.1			
	5	1975.4	19.0			
84	1	2021.3	17.1	**17.3**	**0.8**	**4.9**
	2	2037.4	16.4			
	3	2021.5	17.1			
	4	2021.5	17.1			
	5	1976.6	18.9			
106	1	2019.5	17.2	**17.4**	**0.8**	**4.8**
	2	2035.6	16.5			
	3	2019.4	17.2			
	4	2019.2	17.2			
	5	1974.7	19.0			

APPENDIX G

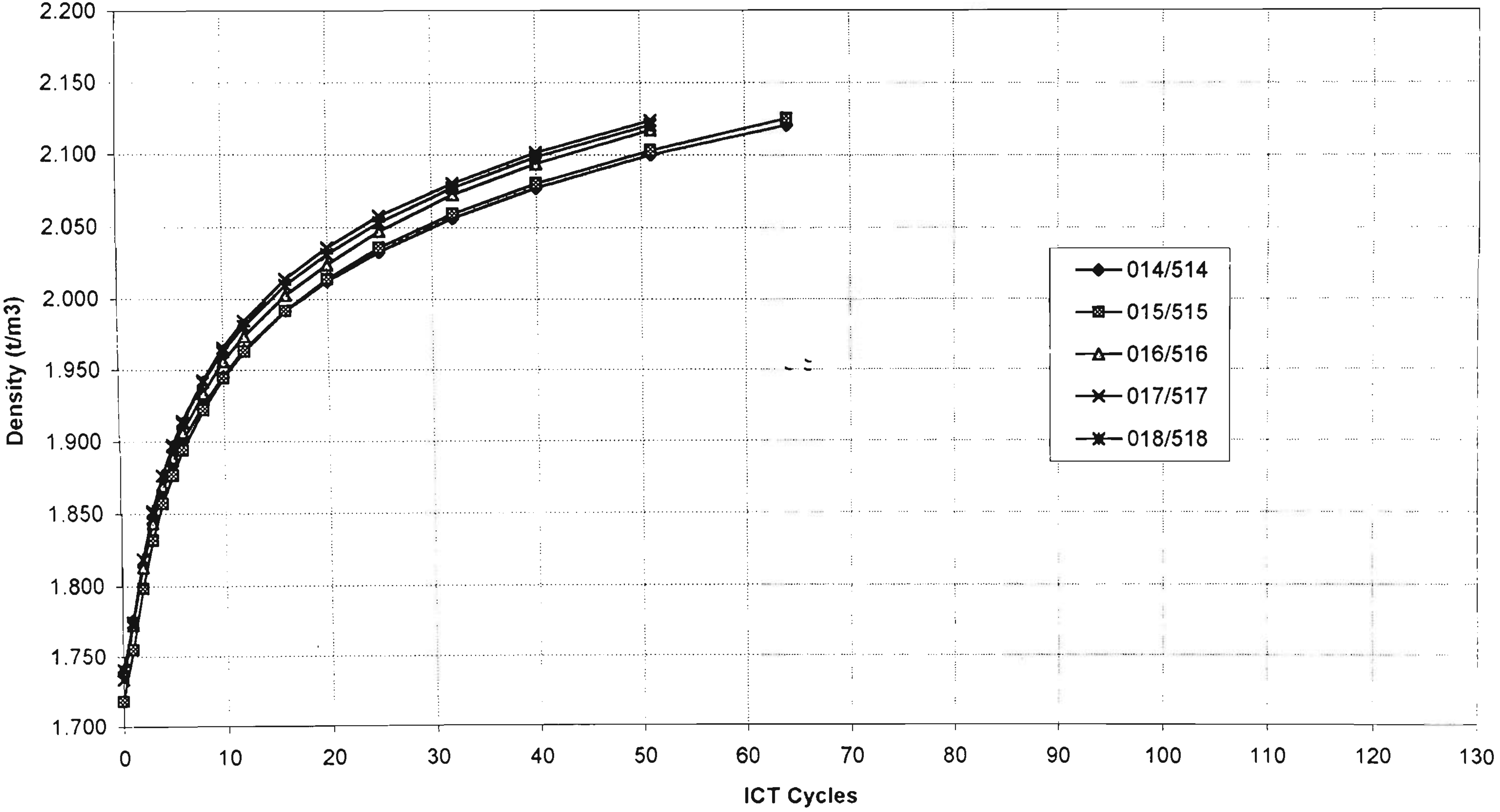
COMPACTION

- **Intensive Compaction Testing Workability Curves For Specimens From Procedure One, Group 1**
- **Intensive Compaction Testing Workability Curves For Specimens From Procedure One, Group 2**
- **Intensive Compaction Testing Workability Curves For Specimens From Procedure One, Group 3**
- **Intensive Compaction Testing Workability Curves For Specimens From Procedure Two**
- **Intensive Compaction Testing Workability Curves For Specimens From Procedure Three**

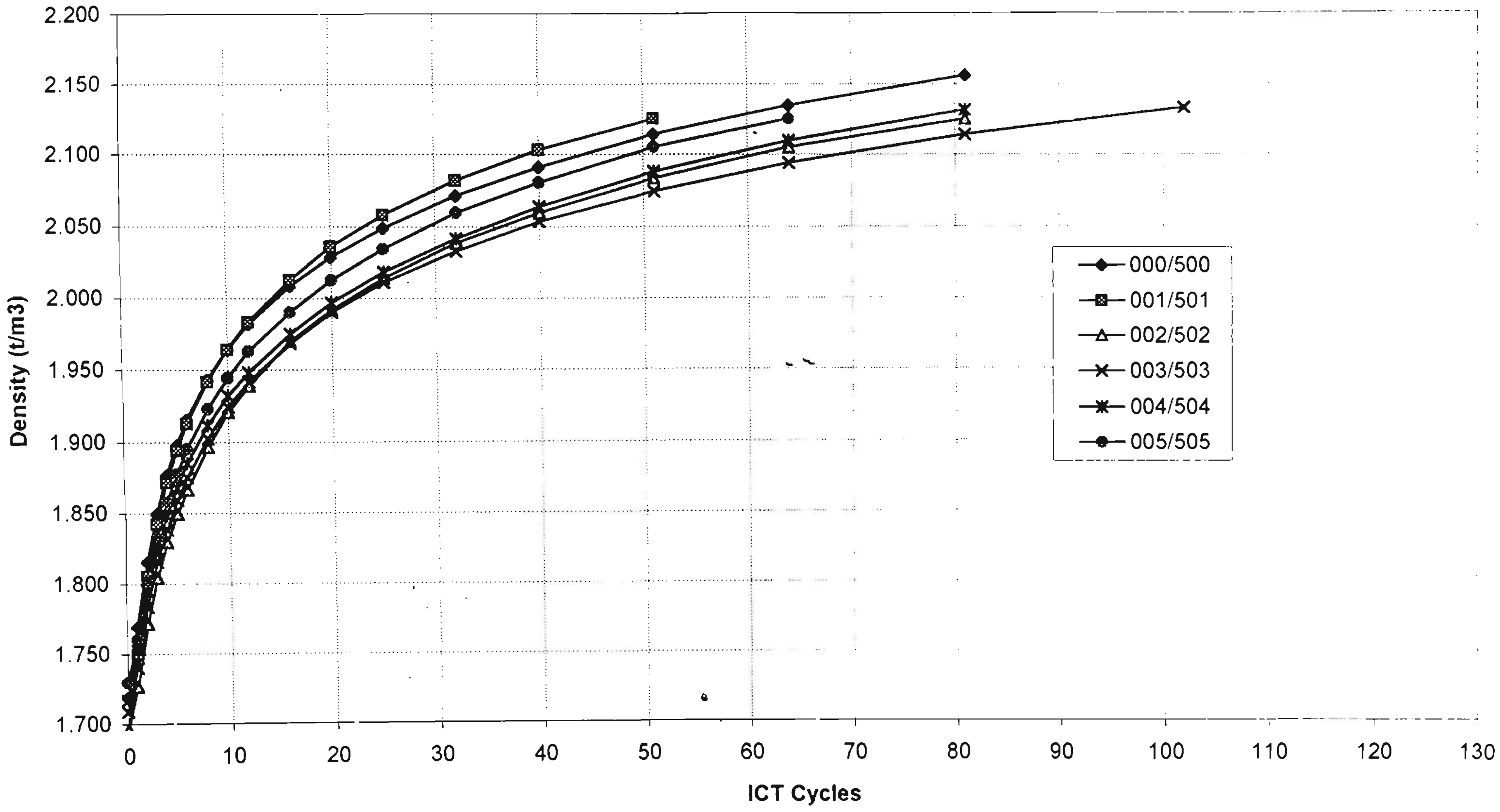
INTENSIVE COMPACTION TESTING WORKABILITY CURVES FOR SPECIMENS FROM PROCEDURE ONE, GROUP 1



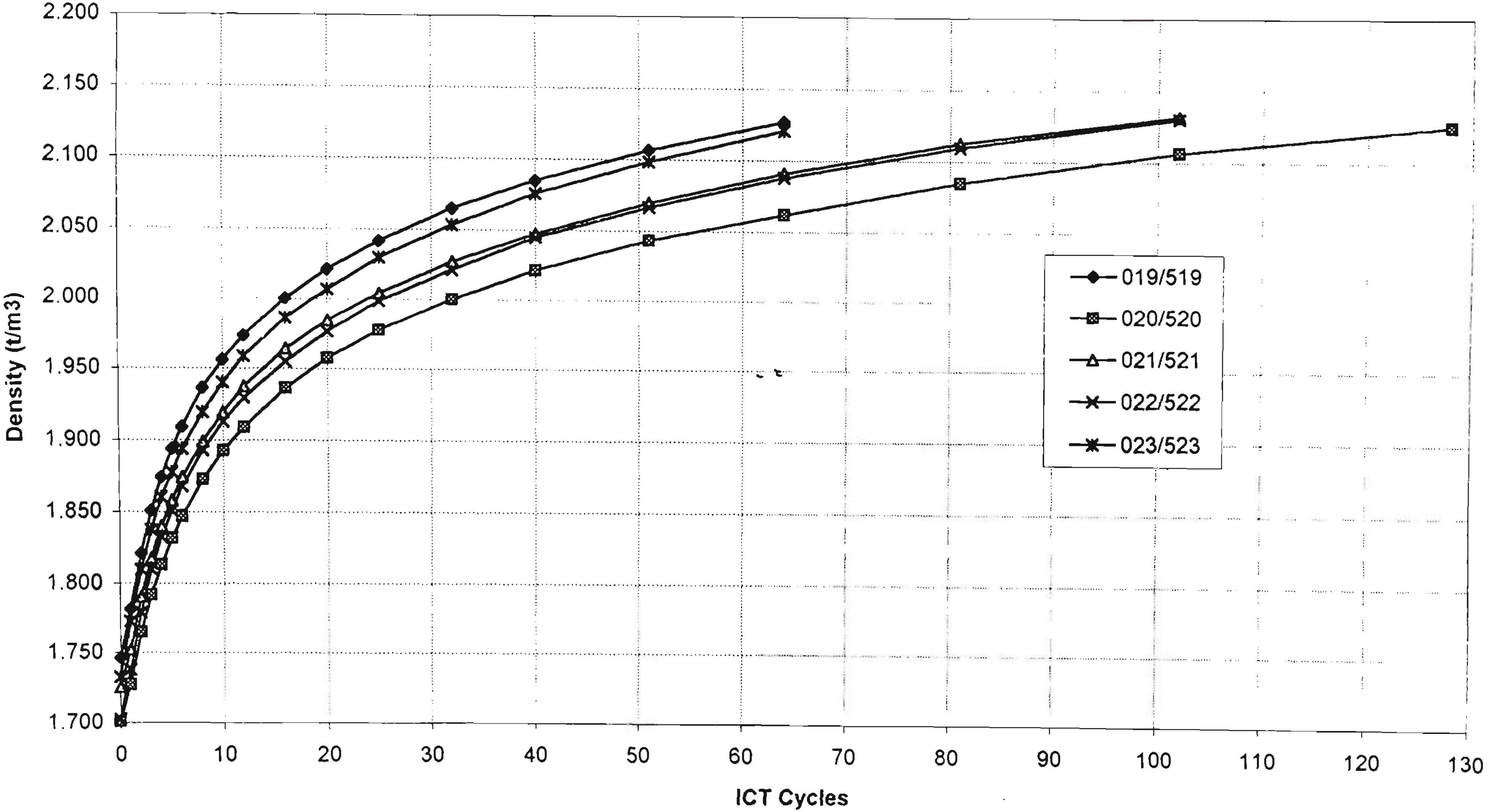
INTENSIVE COMPACTION TESTING WORKABILITY CURVES
FOR SPECIMENS FROM PROCEDURE ONE, GROUP 2



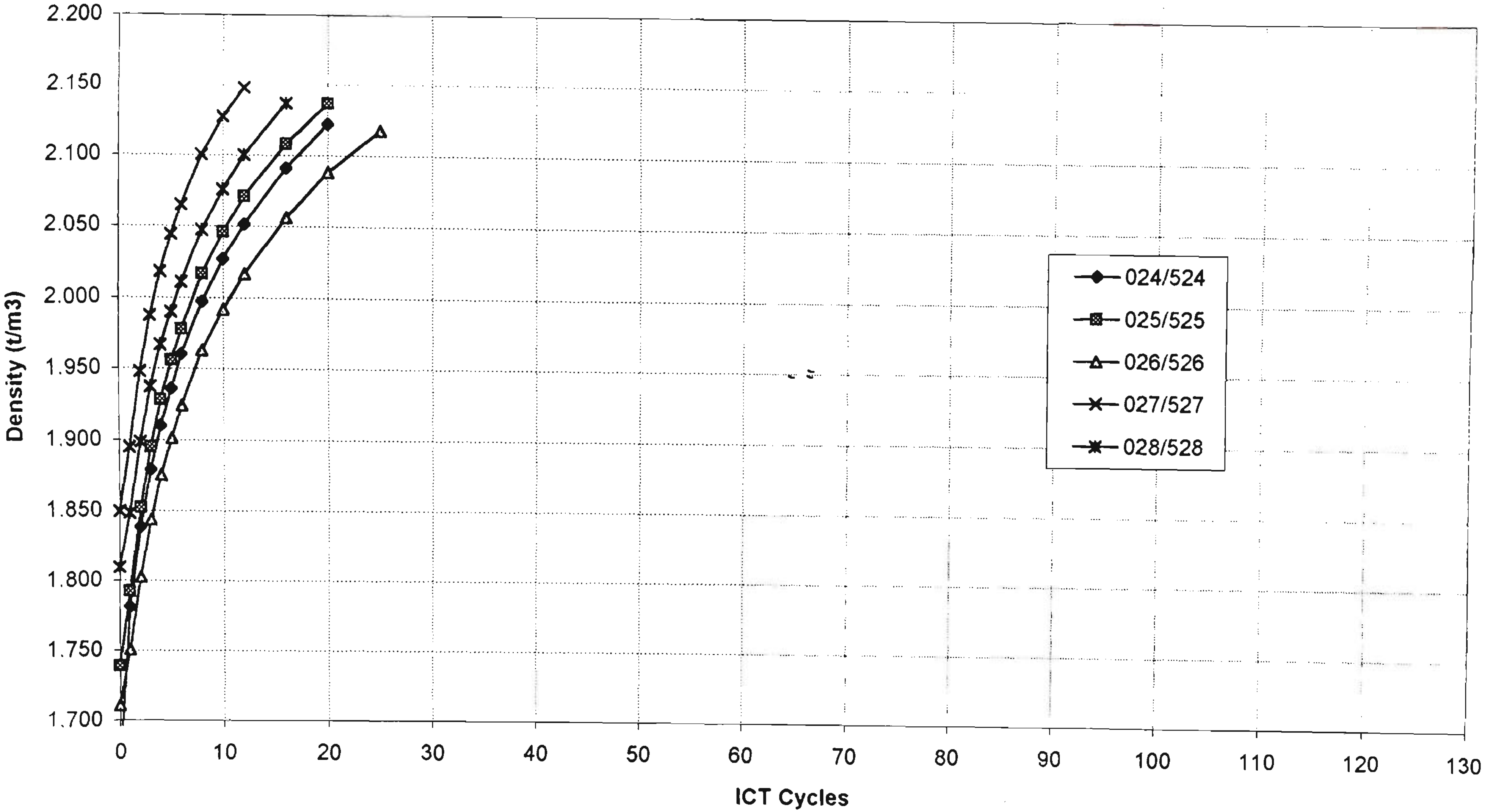
INTENSIVE COMPACTION TESTING WORKABILITY CURVES FOR SPECIMENS FROM PROCEDURE ONE, GROUP 3



INTENSIVE COMPACTION TESTING WORKABILITY CURVES FOR SPECIMENS FROM PROCEDURE TWO



INTENSIVE COMPACTION TESTING WORKABILITY CURVES
FOR SPECIMENS FROM PROCEDURE THREE



APPENDIX H

RESILIENT MODULUS

- **Procedure One, Group 1**
- **Procedure One, Group 2**
- **Procedure One, Group 3**
- **Procedure Two**
- **Procedure Three**

APPENDIX H I

Test results presented in this Appendix represent the mean of five test pulses on each specimen unless otherwise indicated. The specimen mass is the individual mass for each specimen, taken after testing.

PROCEDURE ONE, GROUP 1.

<table>
<tr><td colspan="4">CURING CONDITIONS:</td><td colspan="5">Room Temperature (25°C)</td></tr>
<tr><td colspan="4">ELAPSED TIME:</td><td colspan="5">2 days</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>410</td><td>325.091</td><td>39.10</td><td>50</td><td>32</td><td>130*</td><td>1069.1</td><td>2040.8</td></tr>
</table>

*Resilient modulus is the average of four load pulses.
Mean, SD and C.V. are not presented as only one specimen was tested.

PROCEDURE ONE, GROUP 1.

CURING CONDITIONS:				Room Temperature (25°C)				
ELAPSED TIME:				5 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m³)**
2	408	172.697	38.85	49	32	241	1060.1	2020.6

Mean, SD and C.V. are not presented as only one specimen was tested.

CURING CONDITIONS:				Room Temperature (25°C)				
ELAPSED TIME:				13 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m³)**
3	422	82.879	40.38	50	33	515	1048.3	2007.1

Mean, SD and C.V. are not presented as only one specimen was tested.

PROCEDURE ONE, GROUP 1.

CURING CONDITIONS:				Room Temperature (25°C)				
ELAPSED TIME:				28 days				
SPECIMEN Number	VERTICAL FORCE (N)	TOTAL HORIZONTAL STRAIN (με)	TENSILE STRAIN (kPa)	LOAD RISE TIME (ms)	UNLOAD TIME (ms)	RESILIENT MODULUS (MPa)	SPECIMEN MASS (g)	SPECIMEN BULK DENSITY (kg/m^3)
4	427	82.266	40.68	49	30	521	1048.9	1999.3
5	406	83.019	38.88	49	32	494	1049.4	2009.2
6	408	64.701	38.85	49	34	633	1051.5	2004.2
7	413	91.128	39.44	50	31	456	1049.0	2002.4
8	406	88.193	38.72	50	33	463	1051.3	2006.8
MEAN	412	81.861	39.31	49	32	513	1050.0	2004.4
SD	7.9	9.2	0.7	0.5	1.4	64.2	1.1	3.4
C.V.%	1.9	11.2	1.8	1.0	4.4	12.5	0.1	0.2

PROCEDURE ONE, GROUP 1.

CURING CONDITIONS:				Room Temperature (25°C)				
ELAPSED TIME:				57 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN ($\mu\varepsilon$)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
3	393	72.316	37.64	49	31	548	1045.1	2004.0
4	393	71.932	37.41	51	31	548	1047.7	1997.0
5	396	76.534	37.92	49	31	522	1048.3	2007.1
6	386	66.292	36.79	49	32	584	1050.4	2002.1
7	393	86.548	37.52	49	31	457	1048.0	2000.5
8	395	81.347	37.66	49	32	488	1049.6	2003.6
MEAN	392	75.827	37.49	49	31	525	1048.2	2002.4
SD	3.2	6.6	0.3	0.8	0.5	41.9	1.7	3.1
C.V.%	0.8	8.8	0.9	1.5	1.5	8.0	0.2	0.2

PROCEDURE ONE, GROUP 1.

CURING CONDITIONS:				Room Temperature (25°C)				
ELAPSED TIME:				117 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
3	388	71.476	37.21	51	32	548	1046.0	2005.7
4	391	76.955	37.22	50	32	510	1048.5	1998.5
5	394	74.311	37.68	51	32	534	1049.0	2008.5
6	391	63.058	37.27	51	33	623	1051.2	2003.6
7	397	91.055	37.80	52	32	437	1048.7	1998.9
8	393	72.548	37.47	51	33	544	1050.2	2004.7
MEAN	392	74.901	37.44	51	32	533	1048.9	2003.3
SD	2.8	8.4	0.2	0.6	0.5	55.0	1.6	3.6
C.V.%	0.7	11.2	0.6	1.1	1.5	10.3	0.2	0.2

APPENDIX H II

Test results presented in this Appendix represent the mean of five test pulses on each specimen. The specimen mass is the individual mass for each specimen, taken after testing.

PROCEDURE ONE, GROUP 2.

CURING CONDITIONS:				60°C				
ELAPSED TIME:				24 hours				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	403	74.164	38.60	49	32	549	1059.8	2029.1
2	397	81.444	37.91	50	32	491	1058.3	2023.2
3	403	92.154	38.43	50	32	440	1056.3	2016.4
4	402	78.714	38.44	49	32	515	1058.7	2024.0
5	409	85.659	39.07	49	31	481	1056.8	2020.4
MEAN	403	82.427	38.49	49	32	495	1058.0	2022.6
SD	3.8	6.1	0.4	0.5	0.4	36.2	1.3	4.2
C.V.%	0.9	7.4	1.0	1.0	1.3	7.3	0.1	0.2

PROCEDURE ONE, GROUP 2.

<table>
<tr><td colspan="4">CURING CONDITIONS:</td><td colspan="5">60°C</td></tr>
<tr><td colspan="4">ELAPSED TIME:</td><td colspan="5">4 days</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>395</td><td>41.883</td><td>37.78</td><td>50</td><td>33</td><td>950</td><td>1051.0</td><td>2012.3</td></tr>
<tr><td>2</td><td>397</td><td>45.367</td><td>37.96</td><td>50</td><td>31</td><td>881</td><td>1049.8</td><td>2007.0</td></tr>
<tr><td>3</td><td>397</td><td>50.043</td><td>37.86</td><td>50</td><td>33</td><td>797</td><td>1046.2</td><td>1997.1</td></tr>
<tr><td>4</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>5</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>MEAN</td><td>396</td><td>45.764</td><td>37.87</td><td>50</td><td>32.3</td><td>876</td><td>1049.0</td><td>2005.5</td></tr>
<tr><td>SD</td><td>0.9</td><td>3.3</td><td>0.1</td><td>0.0</td><td>0.9</td><td>62.6</td><td>2.0</td><td>6.3</td></tr>
<tr><td>C.V.%</td><td>0.2</td><td>7.3</td><td>0.2</td><td>0.0</td><td>2.9</td><td>7.1</td><td>0.2</td><td>0.3</td></tr>
</table>

PROCEDURE ONE, GROUP 2.

CURING CONDITIONS:	60°C
ELAPSED TIME:	8 days

SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m³)**
1	405	38.427	38.79	49	32	1064	1051.4	2013.1
2	410	41.002	39.16	51	31	1006	1050.1	2007.6
3	407	48.189	38.86	50	30	849	1046.5	1997.7
4	406	36.473	38.83	49	31	1122	1049.3	2006.0
5	402	48.613	38.44	50	33	833	1048.4	2004.3
MEAN	406	45.541	38.02	50	31.4	975	1049.1	2005.7
SD	2.6	5.0	7.8	0.8	1.0	115.4	1.7	5.0
C.V.%	0.6	11.7	4.7	1.5	3.2	11.8	0.2	0.2

PROCEDURE ONE, GROUP 2.

CURING CONDITIONS:				60°C				
ELAPSED TIME:				15 days				
SPECIMEN Number	VERTICAL FORCE (N)	TOTAL HORIZONTAL STRAIN (µε)	TENSILE STRAIN (kPa)	LOAD RISE TIME (ms)	UNLOAD TIME (ms)	RESILIENT MODULUS (MPa)	SPECIMEN MASS (g)	SPECIMEN BULK DENSITY (kg/m³)
1	400	38.152	38.31	50	32	1057	1050.7	2011.7
2	393	41.518	37.53	50	33	952	1049.5	2006.4
3	397	42.721	37.90	50	33	934	1045.8	1996.3
4	405	39.544	38.68	50	31	1031	1048.7	2004.9
5	403	47.700	38.54	49	31	851	1047.2	2002.0
MEAN	400	41.927	38.19	50	32	965	1048.4	2004.3
SD	4.3	3.3	0.4	0.4	0.9	73.4	1.7	5.1
C.V.%	1.1	7.8	1.1	0.8	2.8	7.6	0.2	0.3

PROCEDURE ONE, GROUP 2.

CURING CONDITIONS:				60°C				
ELAPSED TIME:				30 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	411	36.506	39.32	51	32	1137	1051.6	2013.4
2	412	43.280	39.40	50	33	959	1050.5	2008.3
3	410	43.033	39.15	51	31	958	1046.8	1998.2
4	406	35.350	38.77	50	33	1156	1049.7	2006.8
5	407	43.790	38.92	51	33	937	1048.2	2003.9
MEAN	409	40.392	39.11	50.6	32.4	1029	1049.4	2006.1
SD	2.3	3.7	0.2	0.5	0.8	96.1	1.7	5.0
C.V.%	0.6	9.1	0.6	1.0	2.5	9.3	0.2	0.3

PROCEDURE ONE, GROUP 2.

<table>
<tr><td colspan="4">CURING CONDITIONS:</td><td colspan="5">60°C</td></tr>
<tr><td colspan="4">ELAPSED TIME:</td><td colspan="5">57 days</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>402</td><td>32.549</td><td>38.45</td><td>50</td><td>32</td><td>1245</td><td>1050.2</td><td>2010.8</td></tr>
<tr><td>2</td><td>402</td><td>38.014</td><td>38.39</td><td>51</td><td>32</td><td>1064</td><td>1049.2</td><td>2005.8</td></tr>
<tr><td>3</td><td>402</td><td>36.786</td><td>38.34</td><td>50</td><td>34</td><td>1098</td><td>1045.5</td><td>1995.8</td></tr>
<tr><td>4</td><td>400</td><td>33.898</td><td>38.25</td><td>51</td><td>33</td><td>1189</td><td>1048.3</td><td>2004.1</td></tr>
<tr><td>5</td><td>408</td><td>39.128</td><td>39.02</td><td>50</td><td>31</td><td>1051</td><td>1046.8</td><td>2001.2</td></tr>
<tr><td>MEAN</td><td>403</td><td>36.1</td><td>38.49</td><td>50</td><td>32</td><td>1129.4</td><td>1048.0</td><td>2003.5</td></tr>
<tr><td>SD</td><td>2.7</td><td>2.5</td><td>0.3</td><td>0.5</td><td>1.0</td><td>75.3</td><td>1.7</td><td>5.0</td></tr>
<tr><td>C.V.%</td><td>0.7</td><td>6.9</td><td>0.7</td><td>1.0</td><td>3.1</td><td>6.7</td><td>0.2</td><td>0.2</td></tr>
</table>

PROCEDURE ONE, GROUP 2.

<table>
<tr><td colspan="4">CURING CONDITIONS:</td><td colspan="5">60°C</td></tr>
<tr><td colspan="4">ELAPSED TIME:</td><td colspan="5">113 days</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m^3)</th></tr>
<tr><td>1</td><td>402</td><td>29.018</td><td>38.50</td><td>51</td><td>34</td><td>1397</td><td>1050.4</td><td>2011.1</td></tr>
<tr><td>2</td><td>404</td><td>32.010</td><td>38.59</td><td>51</td><td>32</td><td>1269</td><td>1049.2</td><td>2005.8</td></tr>
<tr><td>3</td><td>401</td><td>31.150</td><td>38.29</td><td>53</td><td>31</td><td>1294</td><td>1045.6</td><td>1996.0</td></tr>
<tr><td>4</td><td>399</td><td>28.518</td><td>38.15</td><td>51</td><td>33</td><td>1410</td><td>1048.4</td><td>2004.3</td></tr>
<tr><td>5</td><td>398</td><td>37.250</td><td>38.06</td><td>51</td><td>33</td><td>1076</td><td>1047.0</td><td>2001.6</td></tr>
<tr><td>MEAN</td><td>401</td><td>31.589</td><td>38.32</td><td>51</td><td>33</td><td>1289</td><td>1048.1</td><td>2003.8</td></tr>
<tr><td>SD</td><td>2.1</td><td>3.1</td><td>0.2</td><td>0.8</td><td>1.0</td><td>120.1</td><td>1.7</td><td>5.0</td></tr>
<tr><td>C.V.%</td><td>0.5</td><td>9.9</td><td>0.5</td><td>1.6</td><td>3.1</td><td>9.3</td><td>0.2</td><td>0.2</td></tr>
</table>

APPENDIX H III

Test results presented in this Appendix represent the mean of five test pulses on each specimen. The specimen mass is the individual mass for each specimen, taken after testing.

PROCEDURE ONE, GROUP 3

<table>
<tr><td colspan="4">CURING CONDITIONS:</td><td colspan="5">90°C</td></tr>
<tr><td colspan="4">ELAPSED TIME AFTER COMPACTION:</td><td colspan="5">24 hours.</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>408</td><td>54.181</td><td>39.02</td><td>49</td><td>35</td><td>759</td><td>1050.7</td><td>2008.7</td></tr>
<tr><td>2</td><td>396</td><td>49.105</td><td>37.92</td><td>49</td><td>33</td><td>814</td><td>1049.7</td><td>2009.8</td></tr>
<tr><td>3</td><td>402</td><td>47.381</td><td>38.45</td><td>50</td><td>32</td><td>854</td><td>1055.3</td><td>2020.5</td></tr>
<tr><td>4</td><td>399</td><td>59.000</td><td>38.10</td><td>49</td><td>32</td><td>680</td><td>1051.7</td><td>2007.6</td></tr>
<tr><td>5</td><td>398</td><td>48.415</td><td>38.11</td><td>49</td><td>33</td><td>830</td><td>1046.6</td><td>2003.9</td></tr>
<tr><td>MEAN</td><td>401</td><td>51.616</td><td>38.32</td><td>49</td><td>33</td><td>787</td><td>1050.8</td><td>2010.1</td></tr>
<tr><td>SD</td><td>4.2</td><td>4.4</td><td>0.4</td><td>0.4</td><td>1.1</td><td>62.1</td><td>2.8</td><td>5.6</td></tr>
<tr><td>C.V.%</td><td>1.0</td><td>8.5</td><td>1.0</td><td>0.8</td><td>3.3</td><td>7.9</td><td>0.3</td><td>0.3</td></tr>
</table>

Results represent the mean of five pulses on each specimen except for the specimen mass and bulk density which are the individual mass and bulk density of each specimen after testing

PROCEDURE ONE, GROUP 3

CURING CONDITIONS:				90°C				
ELAPSED TIME AFTER COMPACTION:				3 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	400	42.790	38.25	51	34	941	1047.5	2002.6
2	404	43.066	38.64	50	33	945	1046.6	2003.9
3	405	41.203	38.74	52	31	990	1051.4	2013.1
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
MEAN	403	42.353	38.54	51	33	959	1048.5	2006.5
SD	2.2	0.8	0.2	0.9	1.3	22.2	2.1	4.7
C.V.%	0.5	1.9	0.5	1.9	3.8	2.3	0.2	0.2

PROCEDURE ONE, GROUP 3

CURING CONDITIONS:				90°C				
ELAPSED TIME AFTER COMPACTION:				7 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	407	44.792	38.87	49	31	913	1046.9	2001.4
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	403	44.052	38.48	49	33	921	1047.7	2000.0
5	406	36.289	38.84	49	33	1127	1042.7	1996.4
MEAN	405	41.711	38.73	49	32	987	1045.8	1999.3
SD	1.7	3.9	0.2	0.0	0.9	99.1	2.2	2.1
C.V.%	0.4	9.2	0.5	0.0	2.9	10.0	0.2	0.1

PROCEDURE ONE, GROUP 3

CURING CONDITIONS:				90°C				
ELAPSED TIME AFTER COMPACTION:				14 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	401	31.270	38.30	51	32	1289	1046.6	2000.9
2	415	34.621	39.70	50	31	1207	1046.1	2002.9
3	401	28.295	38.40	50	33	1429	1050.9	2012.1
4	404	34.938	38.53	50	31	1161	1047.5	1999.6
5	403	31.408	38.60	50	34	1293	1042.4	1995.8
MEAN	405	32.106	38.71	50	32	1276	1046.7	2002.3
SD	5.2	2.5	0.5	0.4	1.2	91.5	2.7	5.4
C.V.%	1.3	7.6	1.3	0.8	3.6	7.2	0.3	0.3

PROCEDURE ONE, GROUP 3

CURING CONDITIONS:				90°C				
ELAPSED TIME AFTER COMPACTION:				28 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	-	-	-	-	-	-	-	-
2	1191	52.457	114.05	51	52	2289	1045.7	2002.1
3	1167	47.139	111.74	51	51	2495	1050.3	2011.0
4	1146	57.393	109.34	50	52	2007	1045.4	1995.6
5	1176	63.591	112.61	50	52	1864	1042.1	1995.3
MEAN	1170	55.145	111.94	51	52	2164	1045.9	2001.0
SD	16.3	6.1	1.7	0.5	0.4	244.9	2.9	6.4
C.V.%	1.4	11.0	1.5	1.0	0.8	11.3	0.3	0.3

PROCEDURE ONE, GROUP 3

CURING CONDITIONS:	90°C
ELAPSED TIME AFTER COMPACTION:	57 days

SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	-	-	-	-	-	-	-	-
2	1200	34.479	114.92	51	52	3508	1045.7	2002.1
3	1197	33.607	114.63	51	52	3590	1050.3	2011.0
4	1180	40.962	112.60	51	52	2894	1045.2	1995.2
5	1186	39.631	113.52	51	51	3017	1042.0	1995.1
MEAN	1191	37.170	113.9	51	52	3252	1045.8	2000.9
SD	8.1	3.2	0.9	0.0	0.4	301.3	3.0	6.5
C.V.%	0.7	8.5	0.8	0.0	0.8	9.3	0.3	0.3

PROCEDURE ONE, GROUP 3

CURING CONDITIONS:				90°C				
ELAPSED TIME AFTER COMPACTION:				118 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	-	-	-	-	-	-	-	-
2	1192	24.412	114.15	51	53	4922	1046.5	2003.7
3	1194	24.604	114.29	52	53	4889	1051.2	2012.7
4	1192	29.503	113.81	52	53	4061	1045.9	1996.5
5	1203	28.446	115.16	52	53	4262	1042.7	1996.4
MEAN	1195	26.741	114.35	52	53	4534	1046.6	2002.3
SD	4.6	2.3	0.5	0.4	0.0	378.9	3.0	6.7
C.V.%	0.4	8.5	0.4	0.8	0.0	8.4	0.3	0.3

APPENDIX H IV

Test results presented in this Appendix represent the mean of five test pulses on each specimen. The specimen mass is the individual mass for each specimen, taken after testing.

PROCEDURE TWO.

CURING CONDITIONS:				Loose Storage at Room Temperature (25°C) for 6 hours and Curing at 90°C				
ELAPSED TIME:				24 hours				
SPECIMEN Number	VERTICAL FORCE (N)	TOTAL HORIZONTAL STRAIN (με)	TENSILE STRAIN (kPa)	LOAD RISE TIME (ms)	UNLOAD TIME (ms)	RESILIENT MODULUS (MPa)	SPECIMEN MASS (g)	SPECIMEN BULK DENSITY (kg/m^3)
1	417	41.609	39.90	51	33	1010	1062.6	2034.5
2	401	33.078	38.24	51	33	1219	1076.9	2055.7
3	410	38.123	39.10	50	32	1080	1067.6	2037.9
4	405	34.185	38.79	50	33	1195	1070.0	2048.7
5	402	43.776	38.34	50	33	922	1062.5	2028.2
MEAN	407	38.154	38.874	50	33	1085	1067.9	2041.0
SD	5.9	4.1	0.6	0.5	0.4	111.6	5.3	9.9
C.V.%	1.4	10.8	1.5	1.0	1.2	10.3	0.5	0.5

PROCEDURE TWO.

CURING CONDITIONS:				Loose Storage at Room Temperature (25°C) for 6 hours and Curing at 90°C				
ELAPSED TIME:				8 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	1154	64.036	110.44	50	52	1821	1060.6	2030.7
2	1166	71.834	111.26	51	52	1632	1074.3	2050.7
3	1174	84.652	112.08	51	52	1394	1065.3	2033.6
4	1171	69.507	112.08	51	51	1698	1068.1	2045.0
5	1171	81.366	111.74	51	53	1446	1059.9	2023.2
MEAN	1167	74.279	111.52	51	52	1598	1065.6	2036.6
SD	7.1	7.6	0.6	0.4	0.6	158.5	5.3	9.9
C.V.%	0.6	10.3	0.6	0.8	1.2	9.9	0.5	0.5

PROCEDURE TWO.

<table>
<tr><th colspan="4">CURING CONDITIONS:</th><th colspan="5">Loose Storage at Room Temperature (25°C) for 6 hours and Curing at 90°C</th></tr>
<tr><th colspan="4">ELAPSED TIME:</th><th colspan="5">22 days</th></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>1164</td><td>59.572</td><td>111.40</td><td>51</td><td>53</td><td>1969</td><td>1060.2</td><td>2029.9</td></tr>
<tr><td>2</td><td>1164</td><td>59.685</td><td>111.07</td><td>51</td><td>53</td><td>1960</td><td>1074.7</td><td>2051.5</td></tr>
<tr><td>3</td><td>1165</td><td>64.209</td><td>111.16</td><td>51</td><td>52</td><td>1823</td><td>1065.6</td><td>2034.1</td></tr>
<tr><td>4</td><td>1182</td><td>58.560</td><td>113.14</td><td>51</td><td>54</td><td>2034</td><td>1068.6</td><td>2046.0</td></tr>
<tr><td>5</td><td>1179</td><td>65.414</td><td>112.51</td><td>52</td><td>52</td><td>1811</td><td>1059.6</td><td>2022.7</td></tr>
<tr><td>MEAN</td><td>1171</td><td>61.488</td><td>111.86</td><td>51</td><td>53</td><td>1919</td><td>1065.7</td><td>2036.8</td></tr>
<tr><td>SD</td><td>8.0</td><td>2.8</td><td>0.8</td><td>0.4</td><td>0.8</td><td>87.5</td><td>5.6</td><td>10.5</td></tr>
<tr><td>C.V.%</td><td>0.7</td><td>4.5</td><td>0.7</td><td>0.8</td><td>1.4</td><td>4.6</td><td>0.5</td><td>0.5</td></tr>
</table>

PROCEDURE TWO.

<table>
<tr><th colspan="4">CURING CONDITIONS:</th><th colspan="5">Loose Storage at Room Temperature (25°C) for 6 hours and Curing at 90°C</th></tr>
<tr><th colspan="4">ELAPSED TIME:</th><th colspan="5">50 days</th></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>1187</td><td>42.142</td><td>113.62</td><td>51</td><td>53</td><td>2838</td><td>1059.4</td><td>2028.4</td></tr>
<tr><td>2</td><td>1197</td><td>40.886</td><td>114.29</td><td>51</td><td>52</td><td>2943</td><td>1074.3</td><td>2050.7</td></tr>
<tr><td>3</td><td>1174</td><td>46.436</td><td>112.08</td><td>50</td><td>52</td><td>2541</td><td>1065.4</td><td>2033.7</td></tr>
<tr><td>4</td><td>1193</td><td>38.689</td><td>114.24</td><td>51</td><td>52</td><td>3109</td><td>1068.3</td><td>2045.4</td></tr>
<tr><td>5</td><td>1191</td><td>40.524</td><td>113.66</td><td>51</td><td>53</td><td>2952</td><td>1059.2</td><td>2021.9</td></tr>
<tr><td>MEAN</td><td>1188</td><td>41.735</td><td>113.58</td><td>51</td><td>52</td><td>2877</td><td>1065.3</td><td>2036.0</td></tr>
<tr><td>SD</td><td>7.9</td><td>2.6</td><td>0.8</td><td>0.4</td><td>0.5</td><td>188.8</td><td>5.7</td><td>10.6</td></tr>
<tr><td>C.V.%</td><td>0.7</td><td>6.2</td><td>0.7</td><td>0.8</td><td>0.9</td><td>6.6</td><td>0.5</td><td>0.5</td></tr>
</table>

PROCEDURE TWO.

CURING CONDITIONS:				Loose Storage at Room Temperature (25°C) for 6 hours and Curing at 90°C				
ELAPSED TIME:				98 days				
SPECIMEN Number	VERTICAL FORCE (N)	TOTAL HORIZONTAL STRAIN (με)	TENSILE STRAIN (kPa)	LOAD RISE TIME (ms)	UNLOAD TIME (ms)	RESILIENT MODULUS (MPa)	SPECIMEN MASS (g)	SPECIMEN BULK DENSITY (kg/m³)
1	1196	30.451	114.53	52	53	3960	1060.1	2029.7
2	1185	30.111	113.13	52	54	3955	1074.9	2051.9
3	1198	35.040	114.33	52	53	3434	1066.2	2035.3
4	1192	29.726	114.10	52	53	4040	1068.8	2046.4
5	1186	33.190	113.23	52	53	3591	1059.8	2023.1
MEAN	1191	31.704	113.86	52	53	3796	1066.0	2037.3
SD	5.2	2.1	0.6	0.0	0.4	238.7	5.7	10.6
C.V.%	0.4	6.5	0.5	0.0	0.8	6.3	0.5	0.5

PROCEDURE TWO.

CURING CONDITIONS:				Loose Storage at Room Temperature (25°C) for 6 hours and Curing at 90°C				
ELAPSED TIME:				106 days				
SPECIMEN Number	VERTICAL FORCE (N)	TOTAL HORIZONTAL STRAIN (με)	TENSILE STRAIN (kPa)	LOAD RISE TIME (ms)	UNLOAD TIME (ms)	RESILIENT MODULUS (MPa)	SPECIMEN MASS (g)	SPECIMEN BULK DENSITY (kg/m^3)
1	1206	29.030	115.45	51	53	4185	1059.3	2028.2
2	1208	28.054	115.34	52	52	4328	1074.1	2050.4
3	1205	31.593	115.01	51	53	3832	1065.3	2033.6
4	1217	28.100	116.46	52	52	4364	1068.3	2045.4
5	1202	28.825	114.72	51	52	4190	1059.2	2021.9
MEAN	1208	29.120	115.40	51	52	4180	1065.2	2035.9
SD	5.1	1.3	0.6	0.5	0.5	188.1	5.7	10.6
C.V.%	0.4	4.4	0.5	1.0	0.9	4.5	0.5	0.5

APPENDIX H V

Test results presented in this Appendix represent the mean of five test pulses on each specimen. The specimen mass is the individual mass for each specimen, taken after testing.

PROCEDURE THREE.

CURING CONDITIONS:				Loose Storage at 60°C for 6 hours and Curing at 90°C				
ELAPSED TIME:				24 hours				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	414	41.356	39.67	50	35	1010	1059.5	2031.6
2	417	42.741	40.26	51	33	992	1060.4	2048.8
3	412	46.429	39.40	51	31	894	1063.0	2032.2
4	411	52.469	39.74	50	32	797	1052.5	2036.6
5	407	68.563	38.87	51	31	597	1041.4	1990.9
MEAN	412	50.312	39.59	51	32	858	1055.4	2028.0
SD	3.3	9.9	0.5	0.5	1.5	151.1	7.8	19.6
C.V.%	0.8	19.7	1.1	1.0	4.6	17.6	0.7	1.0

PROCEDURE THREE.

CURING CONDITIONS: Loose Storage at 60°C for 6 hours and Curing at 90°C

ELAPSED TIME: 7 days

SPECIMEN Number	VERTICAL FORCE (N)	TOTAL HORIZONTAL STRAIN (με)	TENSILE STRAIN (kPa)	LOAD RISE TIME (ms)	UNLOAD TIME (ms)	RESILIENT MODULUS (MPa)	SPECIMEN MASS (g)	SPECIMEN BULK DENSITY (kg/m^3)
1	1164	73.305	111.57	51	52	1604	1054.3	2021.7
2	1184	85.244	112.65	52	52	1392	1054.4	2038.1
3	1167	105.387	111.57	52	52	1116	1058.2	2023.0
4	1168	89.965	113.02	51	53	1325	1046.0	2024.0
5	1163	117.249	111.19	51	52	1001	1033.8	1976.4
MEAN	1169	94.230	112.00	51	52	1288	1049.3	2016.6
SD	7.6	15.4	0.7	0.5	0.4	211.7	8.7	21.0
C.V.%	0.7	16.4	0.6	1.0	0.8	16.4	0.8	1.0

PROCEDURE THREE.

CURING CONDITIONS:				Loose Storage at 60°C for 6 hours and Curing at 90°C				
ELAPSED TIME:				22 days				
SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	1185	53.983	113.60	51	51	2215	1054.0	2021.1
2	1186	61.691	114.60	50	52	1956	1054.4	2037.2
3	1178	71.951	112.63	51	51	1649	1057.7	2022.1
4	1172	62.652	113.37	51	52	1905	1045.6	2023.3
5	1183	84.463	113.11	51	53	1410	1033.3	1975.4
MEAN	1181	66.948	113.46	51	52	1827	1049.0	2015.8
SD	5.2	10.5	0.7	0.4	0.8	275.3	8.8	21.0
C.V.%	0.4	15.6	0.6	0.8	1.4	15.1	0.8	1.0

PROCEDURE THREE.

<table>
<tr><th colspan="4">CURING CONDITIONS:</th><td colspan="5">Loose Storage at 60°C for 6 hours and Curing at 90°C</td></tr>
<tr><th colspan="4">ELAPSED TIME:</th><td colspan="5">50 days</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>1198</td><td>38.083</td><td>114.90</td><td>52</td><td>53</td><td>3176</td><td>1053.8</td><td>2020.7</td></tr>
<tr><td>2</td><td>1187</td><td>37.241</td><td>114.65</td><td>52</td><td>52</td><td>3240</td><td>1054.2</td><td>2036.8</td></tr>
<tr><td>3</td><td>1187</td><td>47.308</td><td>113.50</td><td>51</td><td>53</td><td>2525</td><td>1057.2</td><td>2021.1</td></tr>
<tr><td>4</td><td>1177</td><td>39.528</td><td>113.85</td><td>50</td><td>54</td><td>3032</td><td>1043.9</td><td>2020.0</td></tr>
<tr><td>5</td><td>1165</td><td>53.809</td><td>111.38</td><td>51</td><td>52</td><td>2179</td><td>1033.3</td><td>1975.4</td></tr>
<tr><td>MEAN</td><td>1183</td><td>43.194</td><td>113.66</td><td>51</td><td>53</td><td>2830</td><td>1048.5</td><td>2014.8</td></tr>
<tr><td>SD</td><td>11.1</td><td>6.4</td><td>1.3</td><td>0.8</td><td>0.8</td><td>411.2</td><td>8.8</td><td>20.7</td></tr>
<tr><td>C.V.%</td><td>0.9</td><td>14.8</td><td>1.1</td><td>1.1</td><td>1.4</td><td>14.5</td><td>0.8</td><td>1.0</td></tr>
</table>

PROCEDURE THREE.

<table>
<tr><td colspan="4">CURING CONDITIONS:</td><td colspan="5">Loose Storage at 60°C for 6 hours and Curing at 90°C</td></tr>
<tr><td colspan="4">ELAPSED TIME:</td><td colspan="5">84 days</td></tr>
<tr><th>SPECIMEN Number</th><th>VERTICAL FORCE (N)</th><th>TOTAL HORIZONTAL STRAIN (με)</th><th>TENSILE STRAIN (kPa)</th><th>LOAD RISE TIME (ms)</th><th>UNLOAD TIME (ms)</th><th>RESILIENT MODULUS (MPa)</th><th>SPECIMEN MASS (g)</th><th>SPECIMEN BULK DENSITY (kg/m³)</th></tr>
<tr><td>1</td><td>1184</td><td>25.357</td><td>113.50</td><td>52</td><td>53</td><td>4712</td><td>1054.1</td><td>2021.3</td></tr>
<tr><td>2</td><td>1172</td><td>26.264</td><td>113.24</td><td>51</td><td>52</td><td>4539</td><td>1054.5</td><td>2037.4</td></tr>
<tr><td>3</td><td>1187</td><td>32.236</td><td>113.50</td><td>52</td><td>52</td><td>3706</td><td>1057.4</td><td>2021.5</td></tr>
<tr><td>4</td><td>1175</td><td>32.718</td><td>113.71</td><td>52</td><td>52</td><td>3658</td><td>1044.7</td><td>2021.5</td></tr>
<tr><td>5</td><td>1193</td><td>45.264</td><td>114.07</td><td>52</td><td>53</td><td>2654</td><td>1033.9</td><td>1976.6</td></tr>
<tr><td>MEAN</td><td>1182</td><td>32.368</td><td>113.60</td><td>52</td><td>52.4</td><td>3854</td><td>1048.9</td><td>2015.7</td></tr>
<tr><td>SD</td><td>7.7</td><td>7.1</td><td>0.3</td><td>0.4</td><td>0.5</td><td>735.6</td><td>8.6</td><td>20.5</td></tr>
<tr><td>C.V.%</td><td>0.7</td><td>22.0</td><td>0.2</td><td>0.8</td><td>0.9</td><td>19.1</td><td>0.8</td><td>1.0</td></tr>
</table>

PROCEDURE THREE.

CURING CONDITIONS:	Loose Storage at 60°C for 6 hours and Curing at 90°C
ELAPSED TIME:	106 days

SPECIMEN Number	**VERTICAL FORCE (N)**	**TOTAL HORIZONTAL STRAIN (με)**	**TENSILE STRAIN (kPa)**	**LOAD RISE TIME (ms)**	**UNLOAD TIME (ms)**	**RESILIENT MODULUS (MPa)**	**SPECIMEN MASS (g)**	**SPECIMEN BULK DENSITY (kg/m^3)**
1	1156	18.636	110.80	51	53	6258	1053.2	2019.5
2	1178	21.596	113.83	51	54	5548	1053.6	2035.6
3	1170	26.567	111.86	51	53	4432	1056.3	2019.4
4	1158	25.493	112.00	51	52	4634	1043.5	2019.2
5	1144	34.185	109.31	51	53	3366	1032.9	1974.7
MEAN	1161	25.295	111.56	51	53	4848	1047.9	2013.7
SD	11.8	5.3	1.5	0.0	0.6	989.3	8.7	20.5
C.V.%	1.0	20.8	1.3	0.0	1.2	20.4	0.8	1.0

APPENDIX I

VISCOSITY

- **Viscosity of Bitumen in RAP**
- **Viscosity of Specimens Cured at Room Temperature for 2 Days**
- **Viscosity of Specimens Cured at Room Temperature for 8 Days**
- **Viscosity of Specimens Cured at Room Temperature for 117 Days**
- **Viscosity of Specimens Cured at 60°C for 24 Hours**
- **Viscosity of Specimens Cured at 60°C for 8 Days**
- **Viscosity of Specimens Cured at 60°C for 113 Days**
- **Viscosity of Specimens Stored Loose at 60°C and Cured at 90°C for 24 Hrs.**
- **Viscosity of Specimens Stored Loose at 60°C and Cured at 90°C for 105 Days**

VISCOSITY OF BITUMEN IN RAP

PLATE NUMBER: 1
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0476g
FILM THICKNESS: 79.3m

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
125.9	44	0.0131	5.200	0.9994	5.228
199.7	49	0.0219	5.178	0.9997	5.233
316.8	56	0.0340	5.189	0.9999	5.221
501.7	55	0.0589	5.153	0.9997	5.227
795.2	52	0.0985	5.132	0.9997	5.224
1262.0	39	0.1557	5.137	0.9995	5.233

LOG (VIS) = 5.2271 **SHEAR RATE** = 0.005
CORR. COEFF = 0.9996 **GRADIENT** = 0.926

PLATE NUMBER: 2
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0491g
FILM THICKNESS: 81.8m

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
199.7	51	0.0198	5.219	0.9999	5.256
316.8	50	0.0342	5.185	0.9999	5.273
501.7	47	0.0570	5.165	0.9999	5.270
795.2	53	0.0921	5.159	0.9999	5.268
1262.0	38	0.1564	5.132	0.9999	5.268
1999.4	43	0.2622	5.110	0.9998	5.267

LOG (VIS) = 5.2678 **SHEAR RATE** = 0.005
CORR. COEFF = 0.9999 **GRADIENT** = 0.910

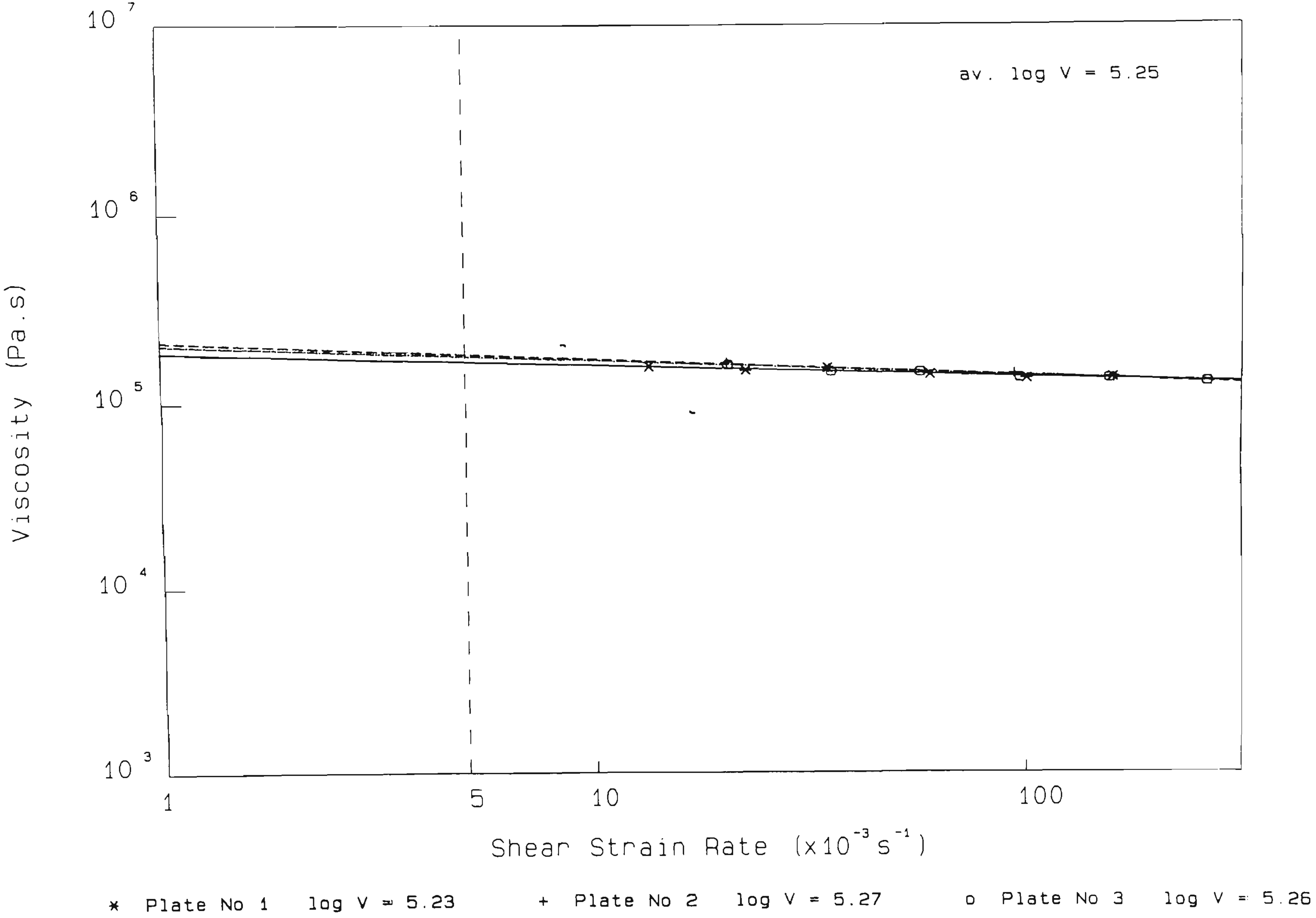
PLATE NUMBER: 3
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0500g
FILM THICKNESS: 83.3m

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
199.7	45	0.0200	5.215	0.9999	5.240
316.8	49	0.0348	5.177	0.9999	5.264
501.7	47	0.0560	5.173	0.9998	5.255
795.2	40	0.0954	5.144	0.9999	5.256
1262.0	38	0.1536	5.140	0.9998	5.258
1999.4	43	0.2574	5.118	0.9997	5.258

LOG (VIS) = 5.2557 **SHEAR RATE** = 0.005
CORR. COEFF = 0.9998 **GRADIENT** = 0.917

AVERAGE LOG (VISC.) OF 3 REPEATS = **5.25**
AVERAGE VISCOSITY OF 3 REPEATS= **178Kpa.s**

VISCOSITY OF BITUMEN IN RAP



VISCOSITY OF SPECIMENS CURED AT ROOM TEMPERATURE FOR 2 DAYS

PLATE NUMBER: 1
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0533g
FILM THICKNESS: 88.8µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	60	0.0325	3.801	0.9996	3.821
19.9	53	0.0566	3.764	0.9994	3.857
31.7	49	0.0979	3.731	0.9998	3.860
50.2	55	0.1577	3.726	0.9995	3.853
79.6	42	0.2501	3.728	0.9996	3.859
125.9	28	0.4235	3.701	0.9992	3.858

LOG (VIS) = 3.8532
CORR. COEFF = 0.9995
SHEAR RATE = 0.005
GRADIENT = 0.915

PLATE NUMBER: 2
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0549g
FILM THICKNESS: 91.5µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	55	0.0306	3.827	0.9999	3.862
19.9	46	0.0528	3.794	0.9998	3.887
31.7	39	0.0900	3.768	0.9999	3.888
50.2	37	0.1451	3.762	0.9998	3.883
79.6	42	0.2428	3.741	0.9998	3.882
125.9	29	0.3944	3.732	0.9998	3.893

LOG (VIS) = 3.8832
CORR. COEFF = 0.9998
SHEAR RATE = 0.005
GRADIENT = 0.908

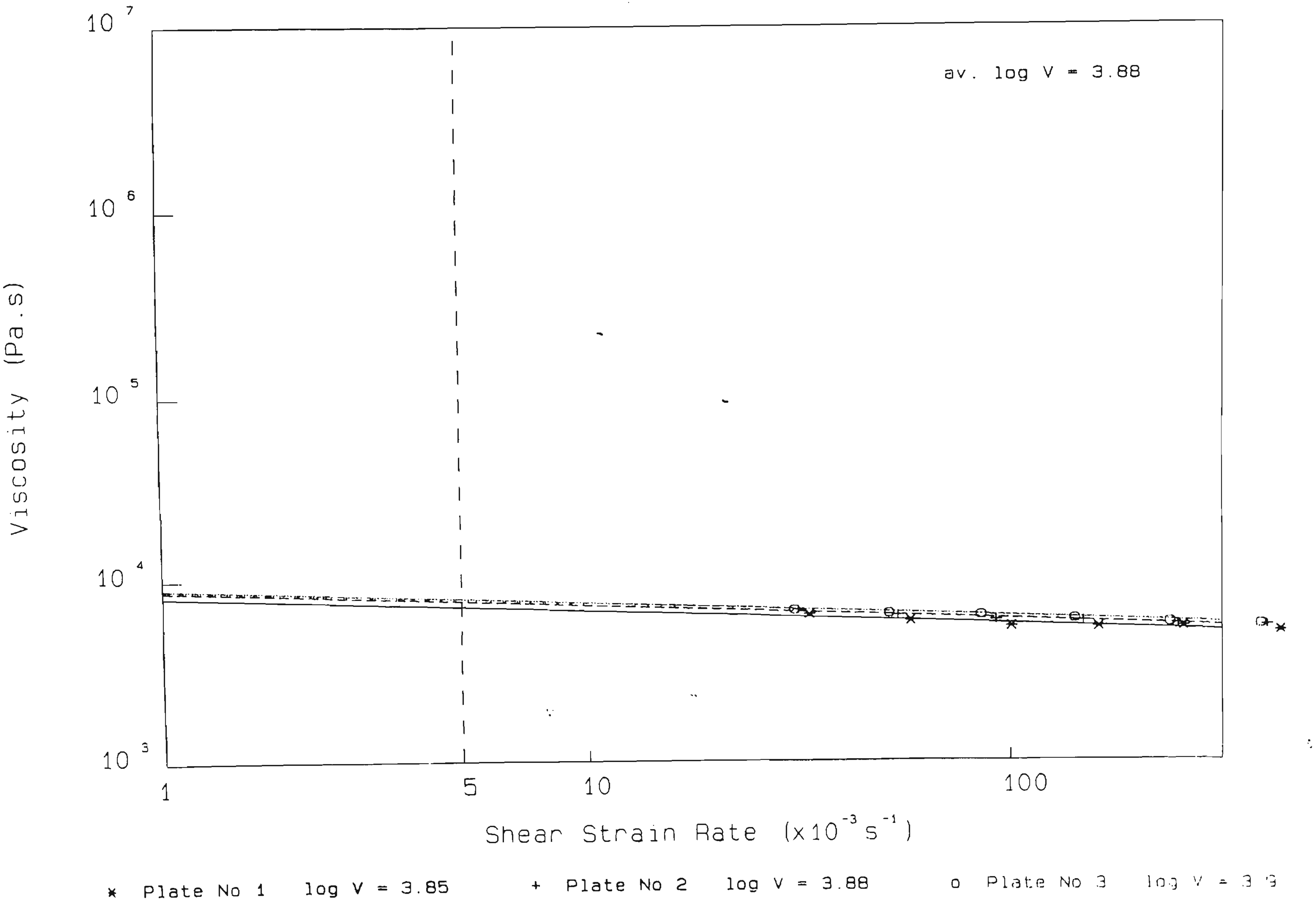
PLATE NUMBER: 3
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0432g
FILM THICKNESS: 72.0µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	57	0.0301	3.835	1.0000	3.897
19.9	54	0.0505	3.814	1.0000	3.900
31.7	48	0.0834	3.801	1.0000	3.897
50.2	45	0.1389	3.781	1.0000	3.898
79.6	50	0.2332	3.758	1.0000	3.897
125.9	36	0.3824	3.745	1.0000	3.900

LOG (VIS) = 3.8982
CORR. COEFF = 1.0000
SHEAR RATE = 0.005
GRADIENT = 0.916

AVERAGE LOG (VISC.) OF 3 REPEATS = **3.88**
AVERAGE VISCOSITY OF 3 REPEATS = **8kPa.s**

VISCOSITY OF SPECIMENS CURED AT ROOM TEMPERATURE FOR 2 DAYS



VISCOSITY OF SPECIMENS CURED AT ROOM TEMPERATURE FOR 8 DAYS

PLATE NUMBER:	1
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0534g
FILM THICKNESS:	89.0µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	51	0.0303	3.831	0.9996	3.866
19.9	47	0.0524	3.797	0.9996	3.891
31.7	41	0.0862	3.786	0.9997	3.885
50.2	37	0.1491	3.750	0.9999	3.885
79.6	44	0.2328	3.759	0.9997	3.890
125.9	30	0.3893	3.738	0.9995	3.892

LOG (VIS)	=	3.8857	**SHEAR RATE**	=	0.005
CORR. COEFF	=	0.9997	**GRADIENT**	=	0.913

PLATE NUMBER:	2
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0543g
FILM THICKNESS:	90.5µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	58	0.0276	3.872	0.9998	3.917
19.9	49	0.0480	3.835	0.9999	3.939
31.7	43	0.0790	3.824	0.9998	3.931
50.2	40	0.1317	3.804	0.9998	3.931
79.6	46	0.2135	3.797	0.9999	3.935
125.9	31	0.3676	3.762	0.9998	3.925

LOG (VIS)	=	3.9308	**SHEAR RATE**	=	0.005
CORR. COEFF	=	0.9998	**GRADIENT**	=	0.918

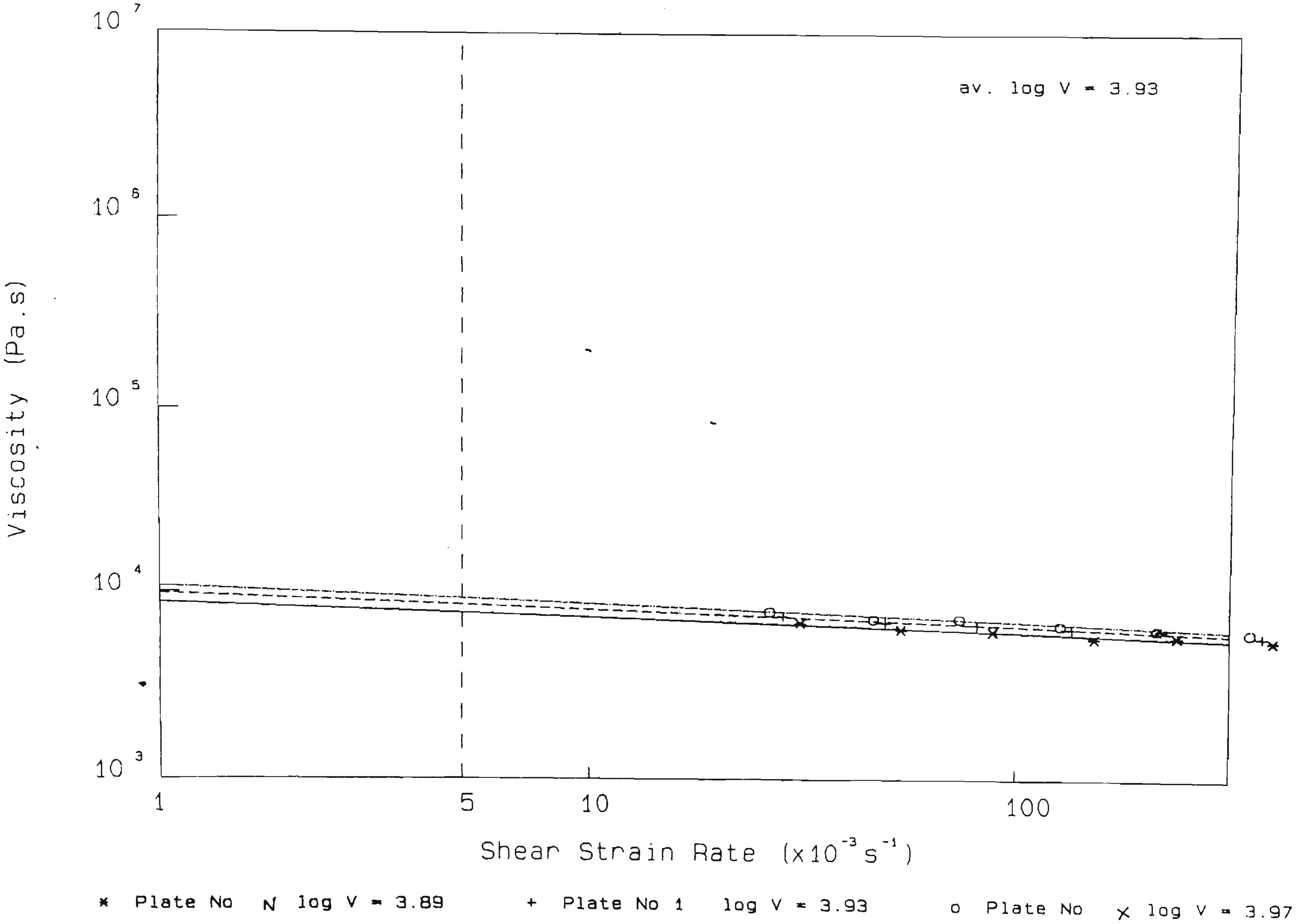
PLATE NUMBER:	3
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0535g
FILM THICKNESS:	89.2µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	41	0.0258	3.901	0.9997	3.954
19.9	51	0.0454	3.860	0.9999	3.976
31.7	46	0.0722	3.863	0.9999	3.961
50.2	42	0.1246	3.828	0.9998	3.965
79.6	47	0.2092	3.805	0.9998	3.964
125.9	33	0.3455	3.789	0.9996	3.968

LOG (VIS)	=	3.9650	**SHEAR RATE**	=	0.005
CORR. COEFF	=	0.9998	**GRADIENT**	=	0.900

AVERAGE LOG (VISC.) OF 3 REPEATS = 3.93
AVERAGE VISCOSITY OF 3 REPEATS = 8kPa.s

VISCOSITY OF SPECIMENS CURED AT ROOM TEMPERATURE FOR 8 DAYS



VISCOSITY OF SPECIMENS CURED AT ROOM TEMPERATURE FOR 117 DAYS

PLATE NUMBER: 1
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0553g
FILM THICKNESS: 92.2µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
19.9	60	0.0209	4.194	0.9996	4.185
31.7	55	0.0380	4.140	0.9992	4.239
50.2	49	0.0629	4.122	0.9993	4.232
79.6	47	0.1012	4.118	0.9992	4.227
125.9	32	0.1737	4.086	0.9992	4.222
199.7	39	0.2680	4.100	0.9993	4.248

LOG (VIS) = 4.2273 **SHEAR RATE** = 0.005
CORR. COEFF = 0.9992 **GRADIENT** = 0.893

PLATE NUMBER: 2
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0521g
FILM THICKNESS: 86.8µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
19.9	45	0.0192	4.231	0.9993	4.261
31.7	49	0.0334	4.196	0.9995	4.281
50.2	46	0.0556	4.176	0.9996	4.277
79.6	53	0.0868	4.185	0.9998	4.273
125.9	56	0.1554	4.134	0.9996	4.269
199.7	43	0.2471	4.135	0.9993	4.281

LOG (VIS) = 4.2742 **SHEAR RATE** = 0.005
CORR. COEFF = 0.9995 **GRADIENT** = 0.907

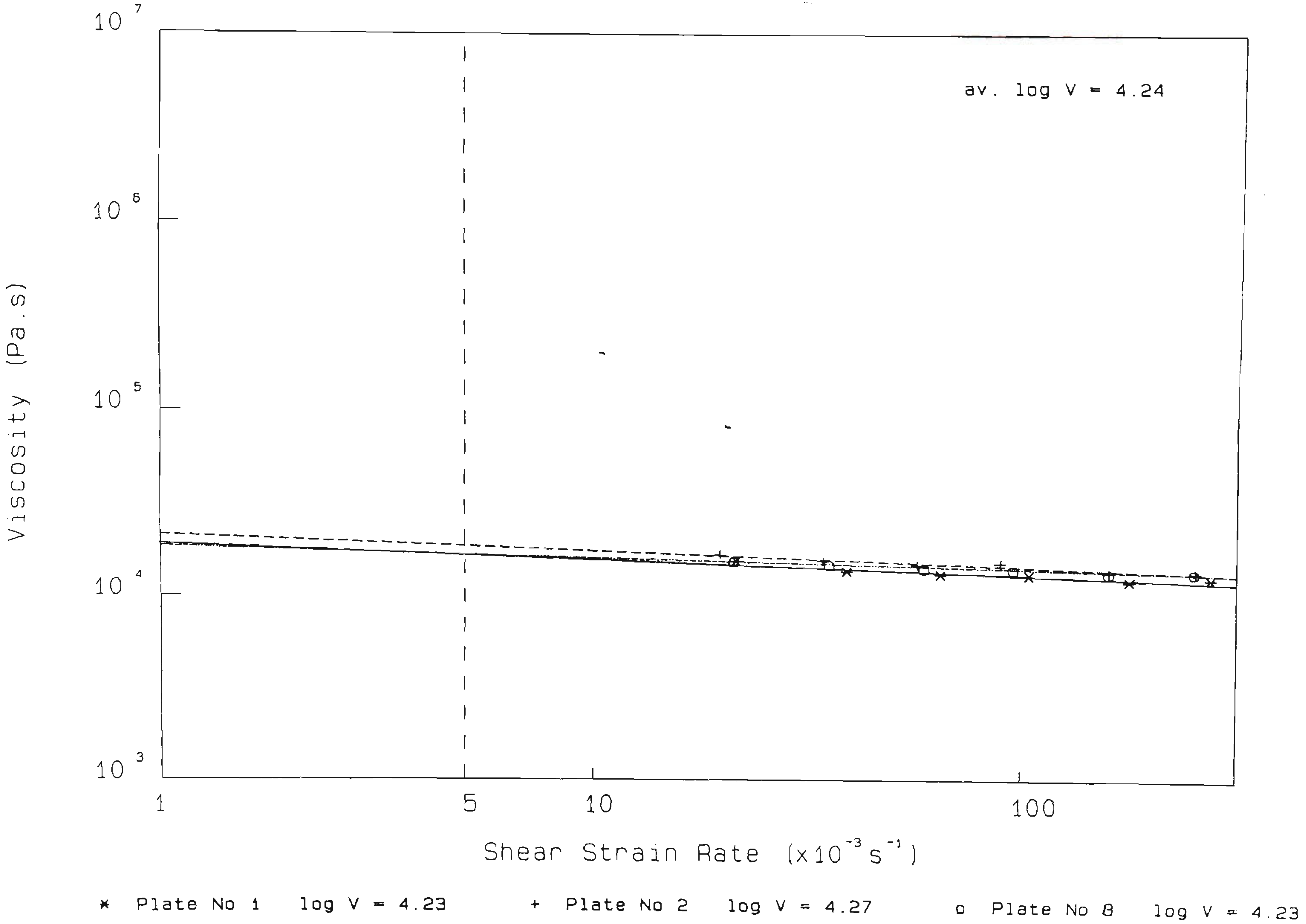
PLATE NUMBER: 3
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0560g
FILM THICKNESS: 93.3µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
19.9	46	0.0207	4.198	0.9998	4.219
31.7	51	0.0347	4.179	0.9998	4.230
50.2	51	0.0579	4.159	0.9999	4.233
79.6	49	0.0932	4.154	0.9999	4.230
125.9	54	0.1557	4.133	0.9999	4.227
199.7	41	0.2466	4.136	0.9999	4.240

LOG (VIS) = 4.2300 **SHEAR RATE** = 0.005
CORR. COEFF = 0.9999 **GRADIENT** = 0.929

AVERAGE LOG (VISC.) OF 3 REPEATS = **4.24**
AVERAGE VISCOSITY OF 3 REPEATS = **18kPa.s**

VISCOSITY OF SPECIMENS CURED AT ROOM TEMPERATURE FOR 117 DAYS



VISCOSITY OF SPECIMENS CURED AT 60°C FOR 24 HOURS

PLATE NUMBER:	1
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0579g
FILM THICKNESS:	96.5μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	56	0.0233	3.946	0.9989	3.947
19.9	51	0.0420	3.894	0.9993	3.995
31.7	58	0.0648	3.910	0.9991	3.974
50.2	42	0.1151	3.862	0.9994	3.977
79.6	50	0.1740	3.886	0.9981	3.984
125.9	35	0.2961	3.856	0.9984	3.981

LOG (VIS)	=	3.9782	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9991	**GRADIENT**	=	0.928

PLATE NUMBER:	2
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0345g
FILM THICKNESS:	57.5μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	55	0.0203	4.006	0.9995	4.006
19.9	58	0.0362	3.958	0.9992	4.050
31.7	54	0.0632	3.921	0.9998	4.050
50.2	50	0.0973	3.935	0.9993	4.042
79.6	47	0.1622	3.916	0.9992	4.045
125.9	52	0.2718	3.894	0.9988	4.047

LOG (VIS)	=	4.0421	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9993	**GRADIENT**	=	0.907

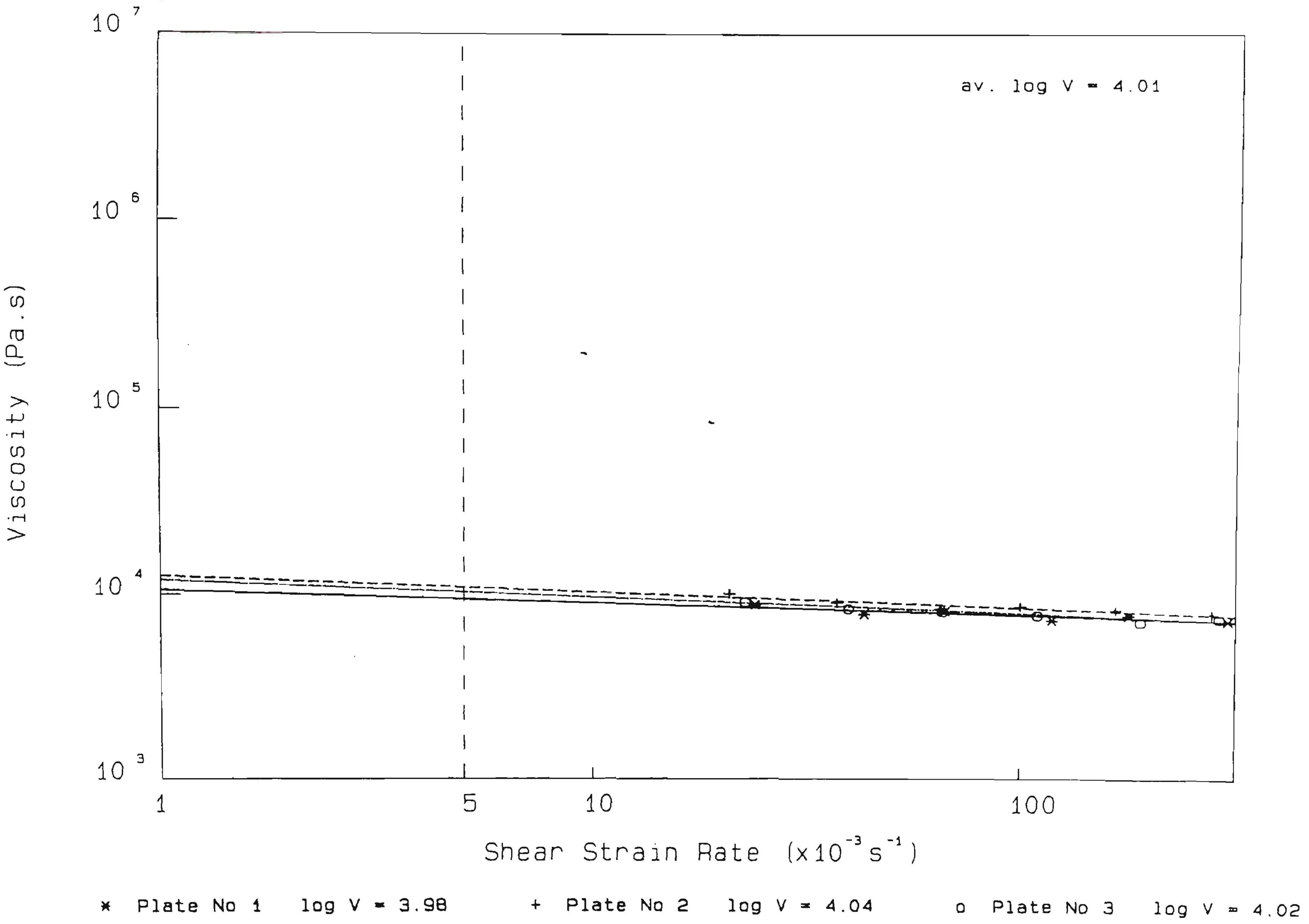
PLATE NUMBER:	3
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0523g
FILM THICKNESS:	87.2μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	46	0.0222	3.968	0.9993	3.996
19.9	56	0.0387	3.929	0.9994	4.022
31.7	50	0.0642	3.914	0.9995	4.017
50.2	47	0.1070	3.894	0.9995	4.016
79.6	51	0.1859	3.857	0.9997	4.008
125.9	39	0.2834	3.875	0.9998	4.037

LOG (VIS)	=	4.0161	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9995	**GRADIENT**	=	0.888

AVERAGE LOG (VISC.) OF 3 REPEATS	=	**4.01**
AVERAGE VISCOSITY OF 3 REPEATS	=	**10kPa.s**

VISCOSITY OF SPECIMENS CURED AT 60°C FOR 24 HOURS



VISCOSITY OF SPECIMENS CURED AT 60°C FOR 8 DAYS

PLATE NUMBER:	1
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0522g
FILM THICKNESS:	87.0μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
19.9	45	0.0230	4.153	0.9995	4.234
31.7	51	0.0372	4.148	0.9997	4.214
50.2	50	0.0643	4.113	0.9997	4.223
79.6	48	0.1035	4.109	0.9998	4.221
125.9	32	0.1840	4.061	0.9998	4.216
199.7	38	0.2943	4.059	0.9995	4.228

LOG (VIS)	=	4.2218	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9997	**GRADIENT**	=	0.900

PLATE NUMBER:	2
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0488g
FILM THICKNESS:	81.3μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
50.2	52	0.0641	4.110	0.9998	4.191
79.6	50	0.1032	4.105	0.9998	4.171
125.9	36	0.1693	4.092	0.9999	4.174
199.7	42	0.2732	4.087	0.9999	4.179
316.8	28	0.4626	4.061	1.0000	4.153

LOG (VIS)	=	4.1738	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9999	**GRADIENT**	=	0.961

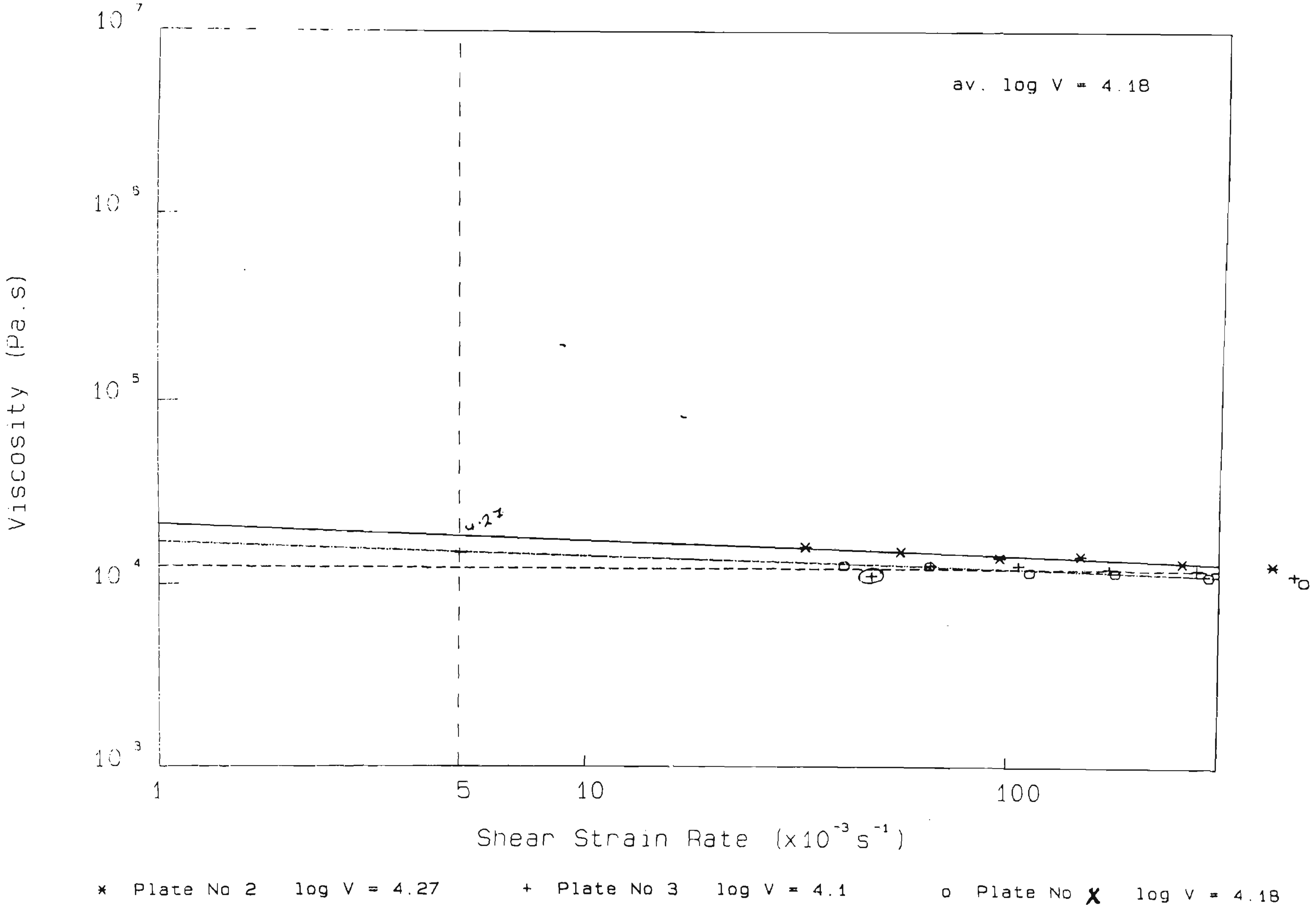
PLATE NUMBER:	3
TEMPERATURE:	45°C
MASS OF BITUMEN:	0.0526g
FILM THICKNESS:	87.7μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
31.7	55	0.0400	4.115	0.9998	4.193
50.2	50	0.0638	4.114	0.9999	4.175
79.6	46	0.1102	4.079	0.9999	4.188
125.9	33	0.1757	4.078	0.9999	4.184
199.7	38	0.2921	4.060	0.9998	4.185
316.8	25	0.4893	4.039	0.9998	4.179

LOG (VIS)	=	4.1839	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9999	**GRADIENT**	=	0.932

AVERAGE LOG (VISC.) OF 3 REPEATS = 4.19
AVERAGE VISCOSITY OF 3 REPEATS = 16kPa.s

VISCOSITY OF SPECIMENS CURED AT 60°C FOR 8 DAYS



VISCOSITY OF SPECIMENS CURED AT 60°C FOR 113 DAYS

PLATE NUMBER: 1
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0516g
FILM THICKNESS: 86.0µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
31.7	47	0.0181	4.460	0.9995	4.478
50.2	51	0.0314	4.422	0.9996	4.503
79.6	49	0.0506	4.417	0.9996	4.494
125.9	54	0.0845	4.396	0.9996	4.495
199.7	58	0.1454	4.363	0.9998	4.489
316.8	46	0.2246	4.377	0.9997	4.511

LOG (VIS) = 4.4953 **SHEAR RATE** = 0.005
CORR.COEFF = 0.9996 **GRADIENT** = 0.902

PLATE NUMBER: 2
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0516g
FILM THICKNESS: 86.0µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
31.7	46	0.0187	4.445	0.9998	4.488
50.2	52	0.0303	4.437	0.9999	4.480
79.6	49	0.0506	4.417	0.9999	4.484
125.9	44	0.0803	4.418	1.0000	4.482
199.7	41	0.1338	4.399	0.9999	4.483
316.8	46	0.2246	4.377	0.9999	4.475

LOG (VIS) = 4.4821 **SHEAR RATE** = 0.005
CORR.COEFF = 0.9999 **GRADIENT** = 0.948

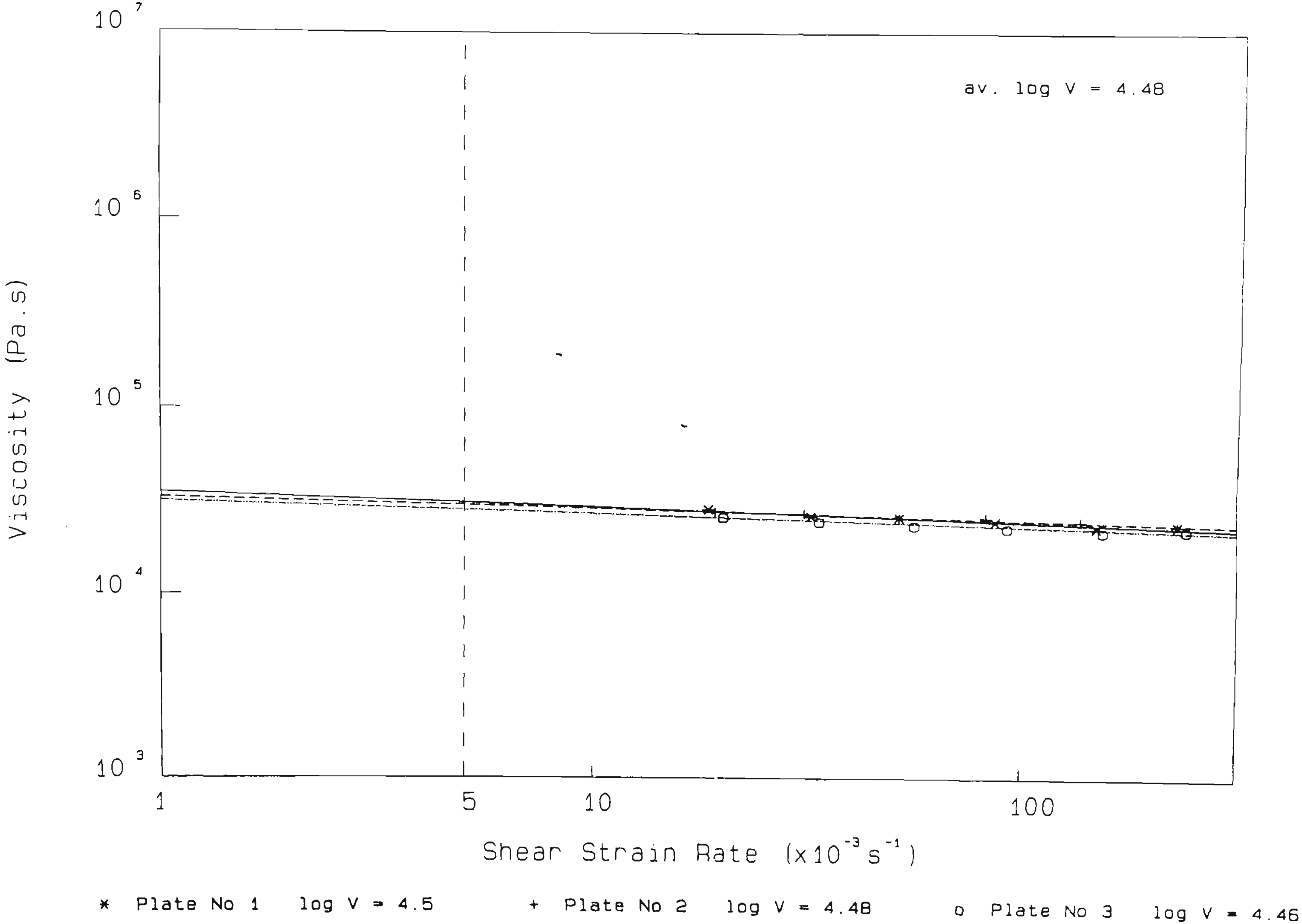
PLATE NUMBER: 3
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0491g
FILM THICKNESS: 81.8µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
31.7	46	0.0197	4.423	0.9997	4.442
50.2	51	0.0330	4.400	0.9997	4.457
79.6	48	0.0550	4.381	0.9998	4.458
125.9	42	0.0905	4.366	0.9998	4.456
199.7	39	0.1509	4.347	0.9998	4.452
316.8	46	0.2361	4.356	1.0000	4.471

LOG (VIS) = 4.4563 **SHEAR RATE** = 0.005
CORR.COEFF = 0.9998 **GRADIENT** = 0.916

AVERAGE LOG (VISC.) OF 3 REPEATS = 4.48
AVERAGE VISCOSITY OF 3 REPEATS = 30kPa.s

VISCOSITY OF SPECIMENS CURED AT 60°C FOR 113 DAYS



VISCOSITY OF SPECIMENS STORED LOOSE AT 60°C AND CURED AT 90°C FOR 24 HRS.

PLATE NUMBER: 1
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0394g
FILM THICKNESS: 65.7µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	55	0.0213	3.984	0.9994	3.993
19.9	58	0.0381	3.936	0.9990	4.035
31.7	48	0.0686	3.886	0.9997	4.042
50.2	43	0.1089	3.886	0.9991	4.033
79.6	40	0.1815	3.867	0.9990	4.033
125.9	46	0.2942	3.859	0.9990	4.050

LOG (VIS) = 4.0328 **SHEAR RATE** = 0.005
CORR.COEFF = 0.9991 **GRADIENT** = 0.876

PLATE NUMBER: 2
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0436g
FILM THICKNESS: 72.7µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	47	0.0257	3.904	0.9998	3.893
19.9	50	0.0462	3.852	0.9994	3.949
31.7	42	0.0764	3.838	0.9994	3.942
50.2	36	0.1263	3.822	0.9994	3.938
79.6	24	0.2061	3.812	0.9992	3.936
125.9	23	0.3243	3.817	0.9994	3.959

LOG (VIS) = 3.9379 **SHEAR RATE** = 0.005
CORR.COEFF = 0.9993 **GRADIENT** = 0.904

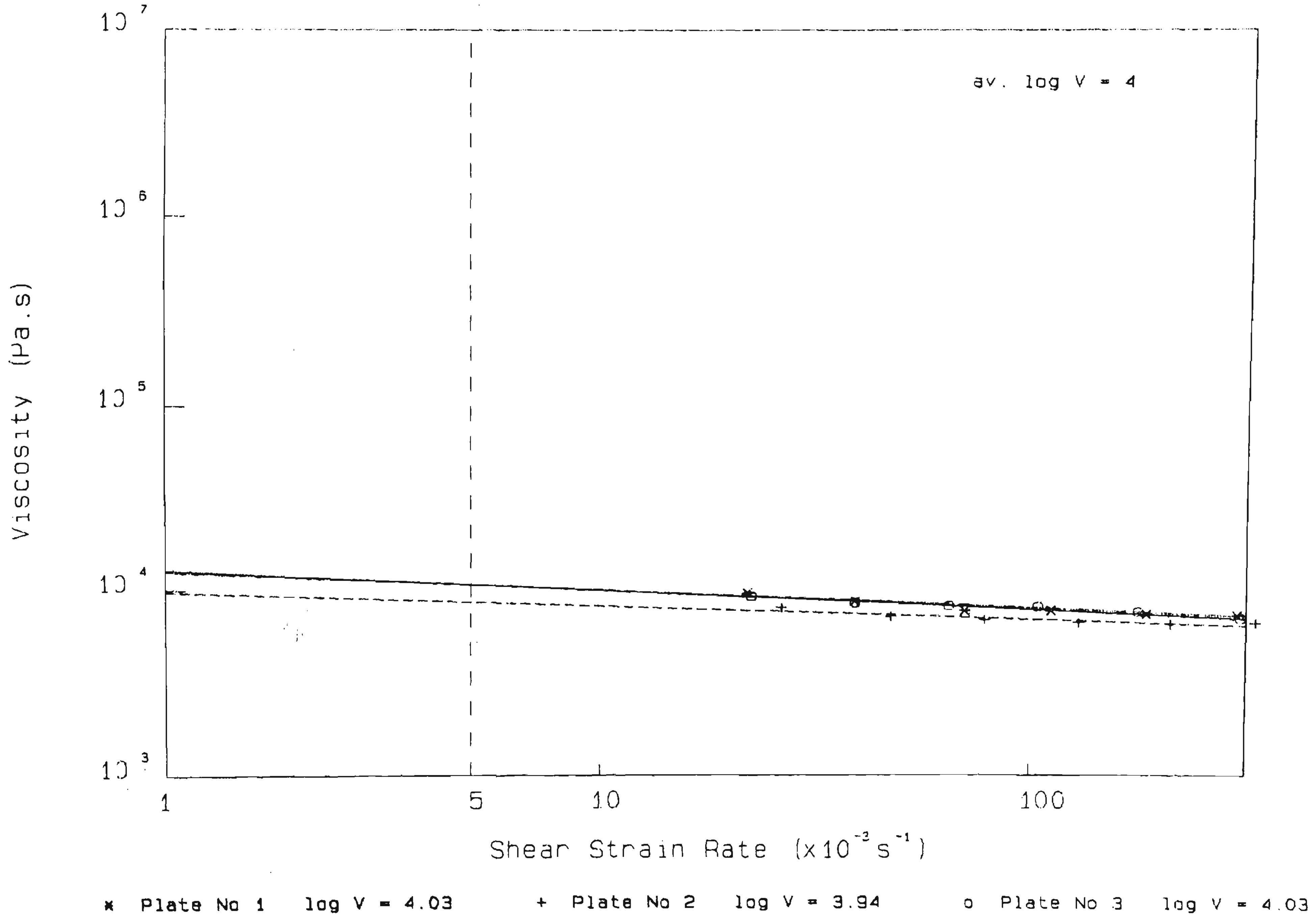
PLATE NUMBER: 3
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0550g
FILM THICKNESS: 91.7µ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
12.5	59	0.0219	3.974	0.9996	4.024
19.9	55	0.0382	3.935	0.9998	4.042
31.7	49	0.0632	3.921	0.9998	4.034
50.2	47	0.1018	3.916	0.9999	4.032
79.6	32	0.1746	3.884	0.9997	4.034
125.9	36	0.3004	3.850	0.9997	4.024

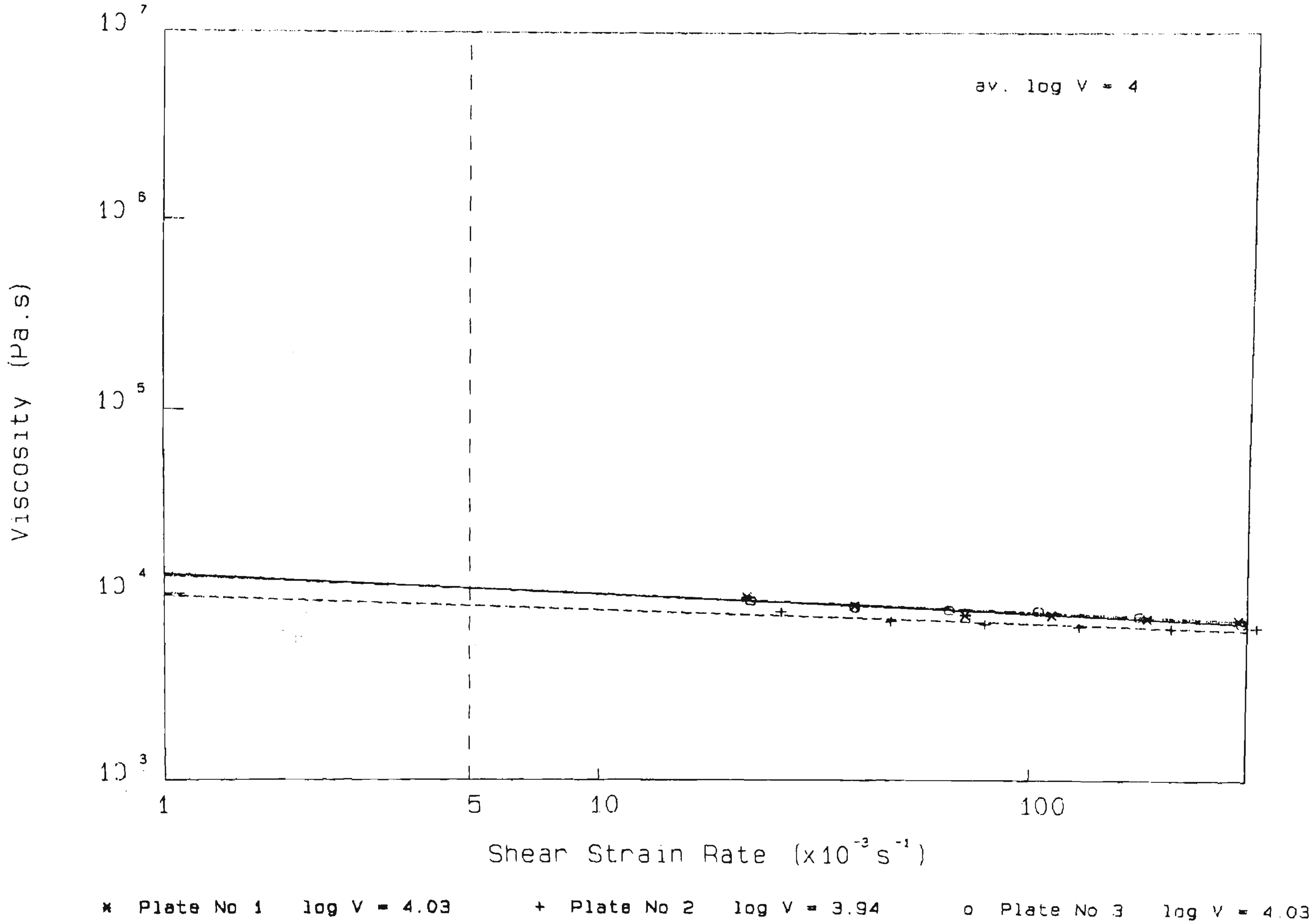
LOG (VIS) = 4.0325 **SHEAR RATE** = 0.005
CORR.COEFF = 0.9998 **GRADIENT** = 0.911

AVERAGE LOG (VISC.) OF 3 REPEATS = 4.00
AVERAGE VISCOSITY OF 3 REPEATS = 10kPa.s

VISCOSITY OF SPECIMENS STORED LOOSE AT 60°C AND CURED AT 90°C FOR 24 HRS.



VISCOSITY OF SPECIMENS STORED LOOSE AT 60°C AND CURED AT 90°C FOR 24 HRS.



VISCOSITY OF SPECIMENS STORED LOOSE AT 60°C AND CURED AT 90°C FOR 105 DAYS

PLATE NUMBER: 1
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0403g
FILM THICKNESS: 67.2μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
1999.4	44	0.0017	7.283	1.0000	7.222
1262.0	53	0.0009	7.348	1.0000	7.184
795.2	57	0.0005	7.390	1.0000	7.168

LOG (VIS)	=	7.1867	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9996	**GRADIENT**	=	0.752

PLATE NUMBER: 2
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0429g
FILM THICKNESS: 71.5μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
1999.4	44	0.0016	7.310	1.0000	7.128
1262.0	50	0.0010	7.329	1.0000	7.214
795.2	42	0.0005	7.407	1.0000	7.268

LOG (VIS)	=	7.2027	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9976	**GRADIENT**	=	0.915

PLATE NUMBER: 3
TEMPERATURE: 45°C
MASS OF BITUMEN: 0.0422g
FILM THICKNESS: 70.3μ

LOAD (g)	ANGLE (deg)	SHEAR RATE	LOG VISCOSITY (Pas)	CORR. COEFF.	LOG VISCOSITY (sh. rt. = 0.5)
1999.4	42	0.0018	7.273	1.0000	6.972
1262.0	45	0.0012	7.245	1.0000	7.162
795.2	42	0.0005	7.400	1.0000	7.345

LOG (VIS)	=	7.1190	**SHEAR RATE**	=	0.005
CORR.COEFF	=	0.9805	**GRADIENT**	=	1.161

AVERAGE LOG (VISC.) OF 3 REPEATS = **7.17**
AVERAGE VISCOSITY OF 3 REPEATS = **14776kPa.s**